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| Title: | Deconstructing Integrated High Energy Density Physics Experiments into Fundamental Models for Validation |
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# Deconstructing Integrated High Energy Density Physics Experiments into Fundamental Models for Validation


**MIPSE seminar**
**Ann Arbor, MI**

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**ICF program manager**
**Los Alamos National Laboratory**

Dec. 5th, 2018

Los Alamos NATIONAL LABORATORY EST.1943

NNSA National Nuclear Security Administration

# Goals for the talk

- **Communicate the excitement of big science**
  - What are some of the big questions?
- **Advertise the LANL ICF/HED program, i.e. recruitment**
- **Provide a strategic program view for the work and how we use the data**


**This work represents a large group of people across multiple programs!**

# One focus of LANL’s high energy density physics effort is mix and burn during the stagnation phase of ICF implosions

- Inertial Confinement Fusion is a grand challenge in big science requiring a large mix of skills that includes participants both nationally and internationally
- While considerable progress has been made towards ignition, challenges remain which require improved implosion performance or larger capsules
- The largest looming questions are, “Is ignition on NIF possible?” and “What is required to achieve ignition?”
- LANL is strategically focuses on the understanding the evolution of hydrodynamics and burn physics for implosions using novel platforms and focused experiments for code validation
- The program looks to bring in capabilities that can improve our ability to quantify and validate our understanding

# Big science requires large cutting edge facilities, a diverse work force, and large budgets

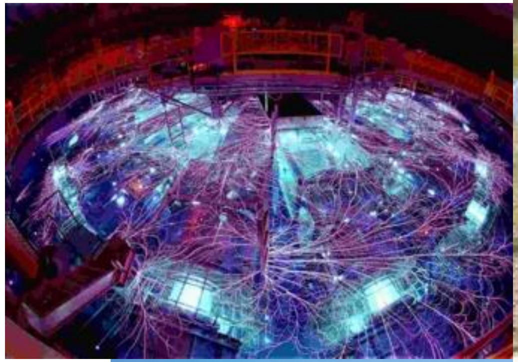
- ***Big staffs***: Grand challenges require cutting edge technology and a large diverse workforce to solve a collection or problems including scientists, engineers, technicians, and skilled crafts.

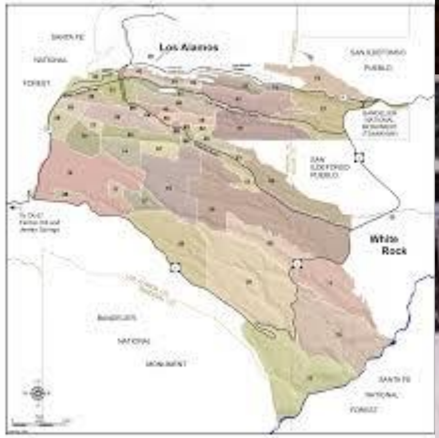
- ***Big machines***: Generating extreme conditions requires enormous energy or spatial scales to reach such conditions such as large pulsed power storage or long path length for particle acceleration

- ***Big laboratories***: Supporting activities with respect to R&D and specialized production drive the need for large laboratories.

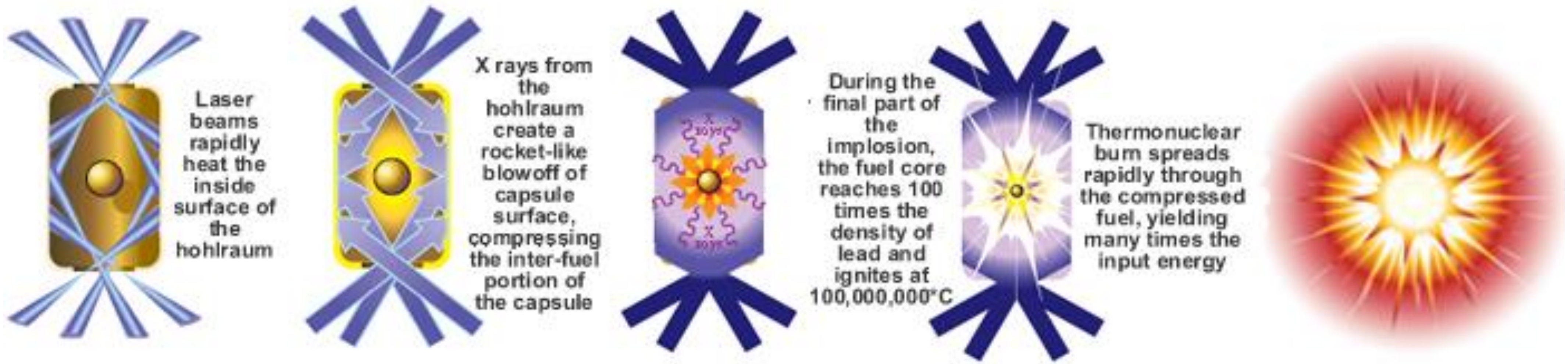
- ***Big budgets***: The combination of the requirements to achieve grand challenges leads to large budgets

Academic and industrial partners provide vital cost effective support






# Indirect Drive Inertial Confinement Fusion converts laser light to x rays using high-Z material driving a Deuterium-Tritium filled capsule to fusion conditions



# Many pieces of physics and engineering must come together to achieve ICF

## Hohlraum

Peak laser Intensities

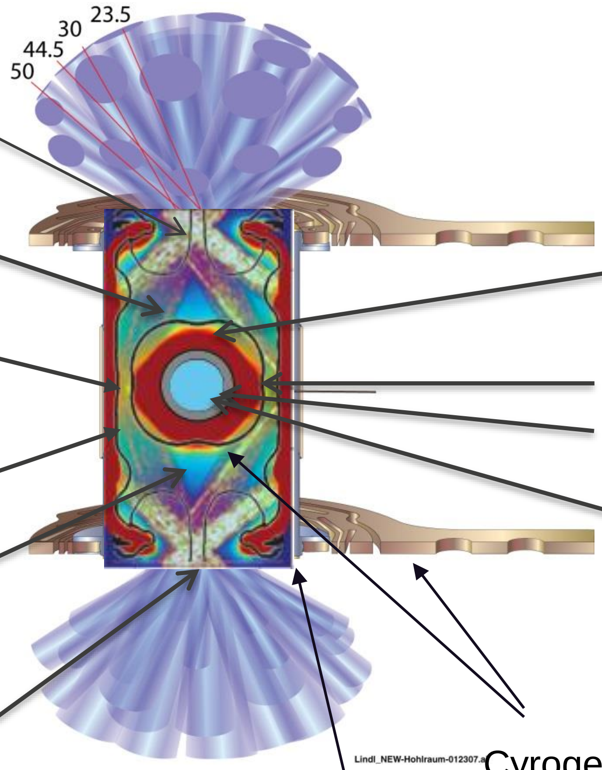
Gas fill species and optimum density

compressed between wall and ablator blowoff (SRS)

Be ablator blowoff (SBS)

Hot Electrons

Cross beam energy transfer




Hydrodynamic Instabilities

Tent/ fill tube defect hydro

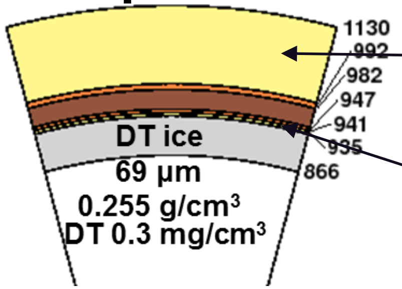
implosion symmetry

Fuel Adiabat

Cyrogenics

Precision Engineering

## Capsule

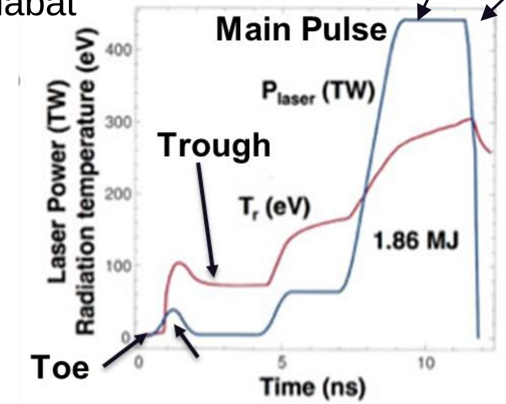



Material Science
EOS/Opacity

Manufacturing

Laser pulse shaping

Power balance



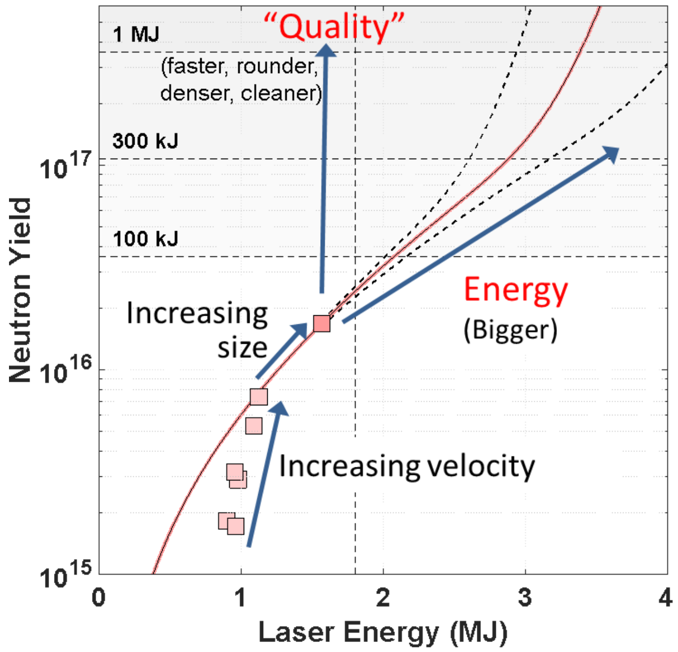

Adiabat:
$\alpha$ = DT ice internal energy/ Fermi energy @ 1000 g/cc

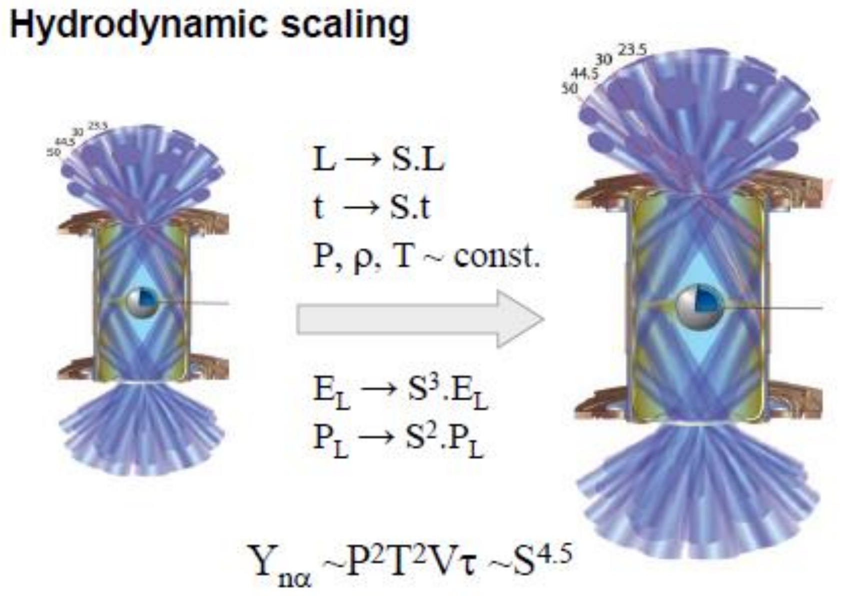
**Diagnostics**
**Computation**

A large pool of expertise is critical for advancing ICF

# What will it take to achieve ignition in the laboratory? Can this be done with NIF?

Can we credibly scale to ignition?




**Not all physics scales linearly with size:**

- Radiation
- Heat conduction
- LPI
- Instability seeds/Richtmyer-Meshkov

No alpha

$$Yield \sim \mathbf{Scale^{4.5}} \times \overbrace{P_{Ablation}^{4/5} \frac{Velocity^8}{Adiabat^2}}^{\text{1D}} \times \overbrace{[Mix < 1]\,[Shape < 1]}^{\text{3D}}$$

How well do we understand the physics for current targets?

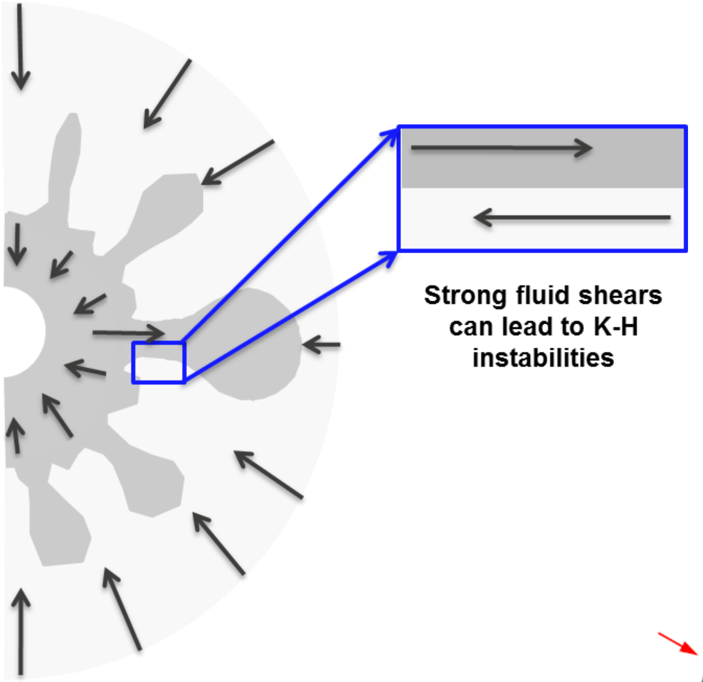
# How do we build credibility for our scaling predictions?

**There are several guidelines that need to be true to trust our predictions:**

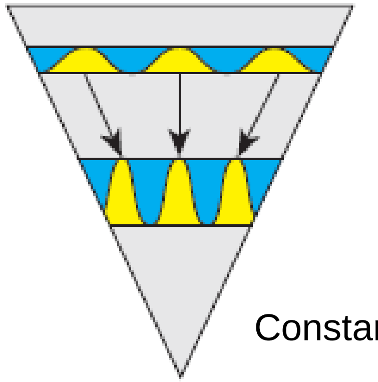
- the calibration and validation of the embedded models is sufficient to give confidence in the prediction;
- the embedded models are being used within their domain of applicability;
- the resulting prediction with its uncertainties is sufficient for the purpose for which the prediction is being made

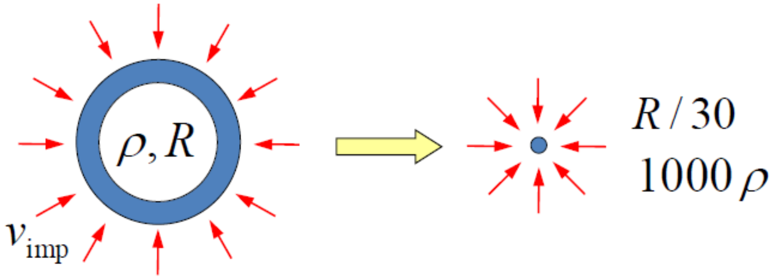
# ICF implosions are inherently hydrodynamically unstable!

- **Different target layer densities**
  - Rayleigh-Taylor
- **Strong Shear flows**
  - Kelvin-Helmoltz
- **Multiple shocks**
  - Richtmyer-Meshkov
- **Models for burn in the presence of mix**
  - burn model



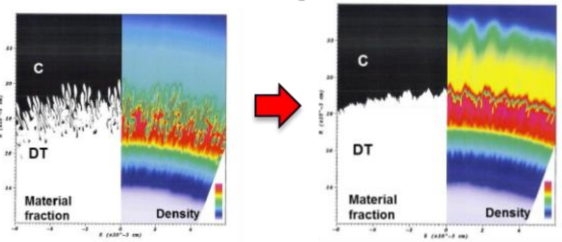

## Convergence Amplified perturbations




Instabilities can mix ablator material into the fuel and degrade and/or prevent ignition

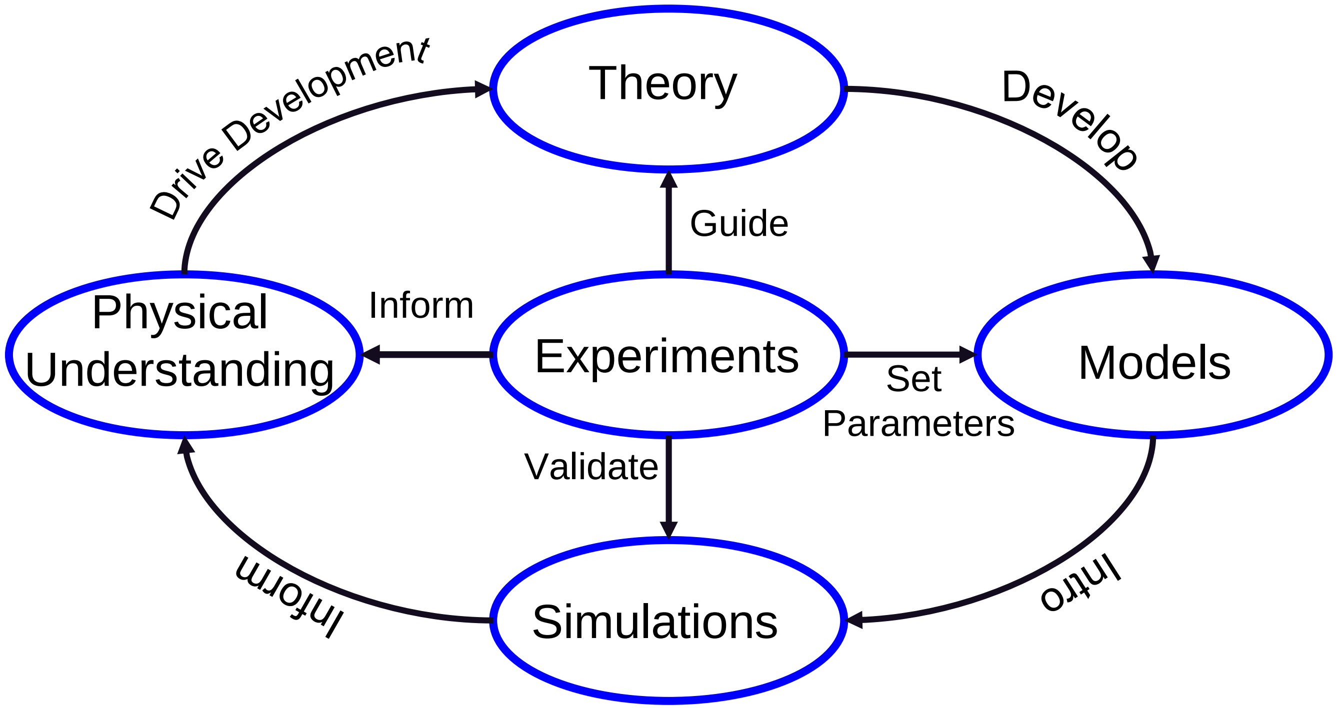
**Interface mixing can affect compression**




**burn fraction**

$$f = 1 - \frac{n_{\text{final}}}{n_{\text{init}}} = \frac{\rho R}{\rho R + 8 m_i c_s / \langle \sigma v \rangle} \cong \frac{\rho R}{\rho R + 6\ \text{g/cm}^2}\ , \quad T_i = 30\ \text{keV}$$

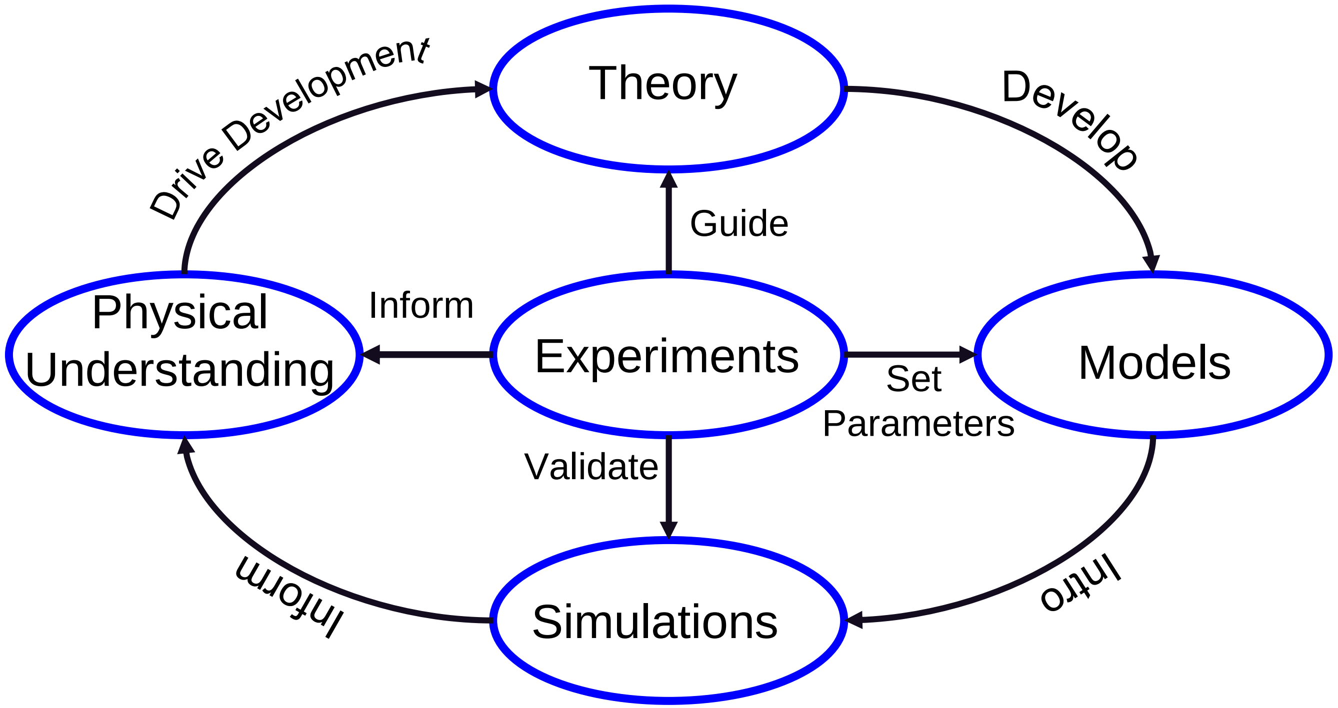
# Advancing our predictive capability requires strong partnerships between theory, computation, and experiment




Experiments:

- Discover
- Validate
- Calibrate

# Advancing our predictive capability requires strong partnerships between theory, computation, and experiment



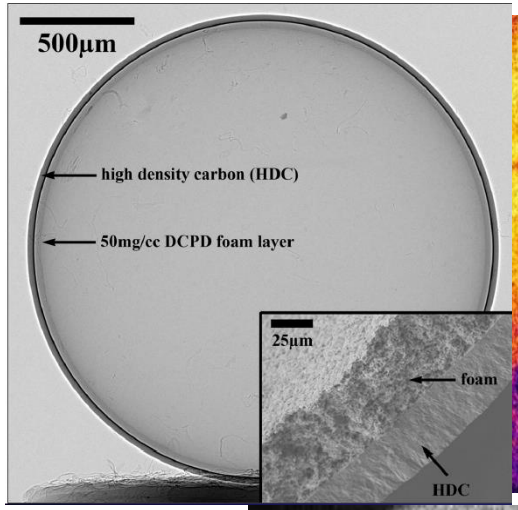

Experiments:
- Discover
- Validate
- Calibrate

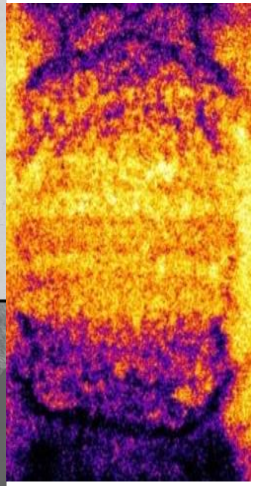
**It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with *experiment*, it's wrong. --Richard Feynman**

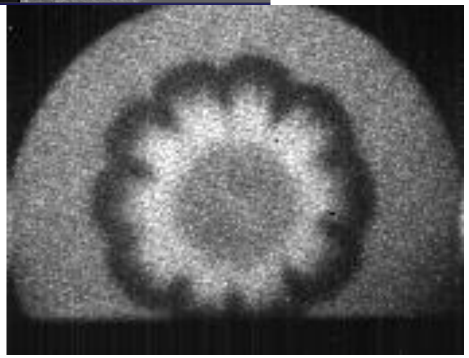
# A principle focus of LANL HEDP program is mix and burning plasmas to validate models for ICF implosions

## This is accomplished using three threads:

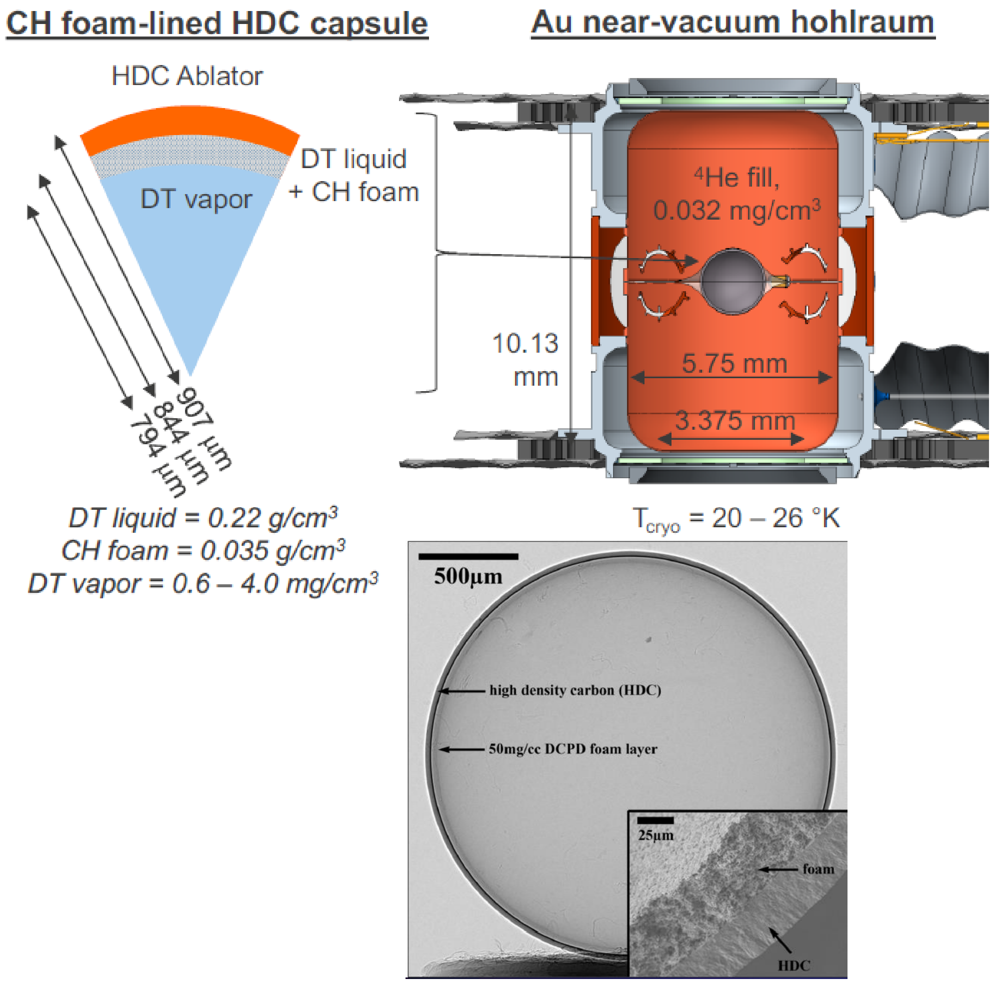
- **Novel implosion platforms to inform performance**
  - Reduced convergence wetted foam targets
  - Double Shell targets
- **Focused experiments for validation**
  - Hydrodynamic mix
    - *Shear driven hydrodynamic instabilities*
    - *Mod Con*
    - *Oblique shock*
    - *Cylinder*
  - Burn model
    - **PDF burn model**
  - Non-hydrodynamic
    - **Kinetic Plasma Effects**
- **Burning Plasma Diagnostics**
  - Neutron imaging, Reaction History, Radio-Chemistry
- **Developing UQ tools**
  - Bayesian Inference Engine

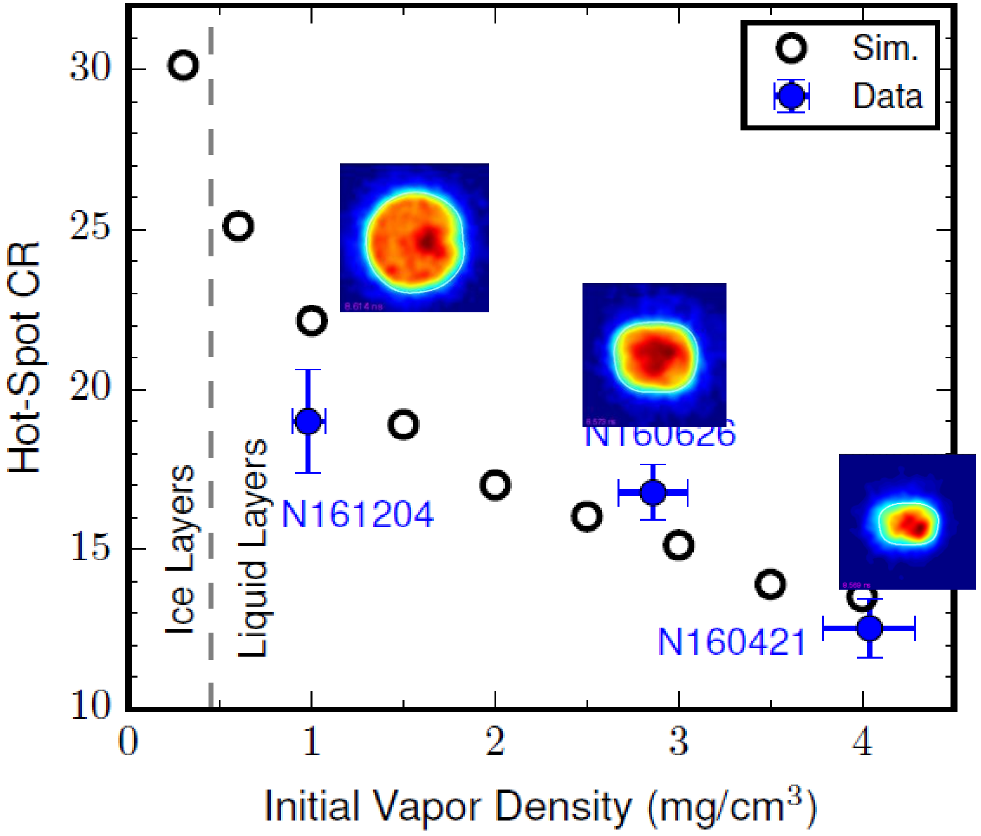




# LANL developed a novel implosion platform to provide insight into the effect of convergence on performance



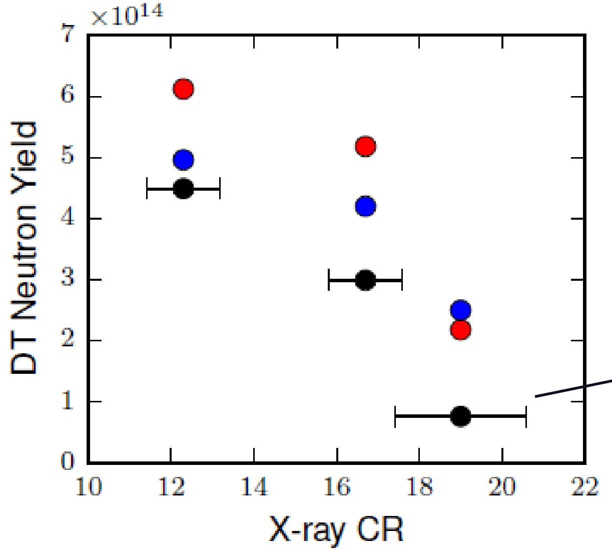



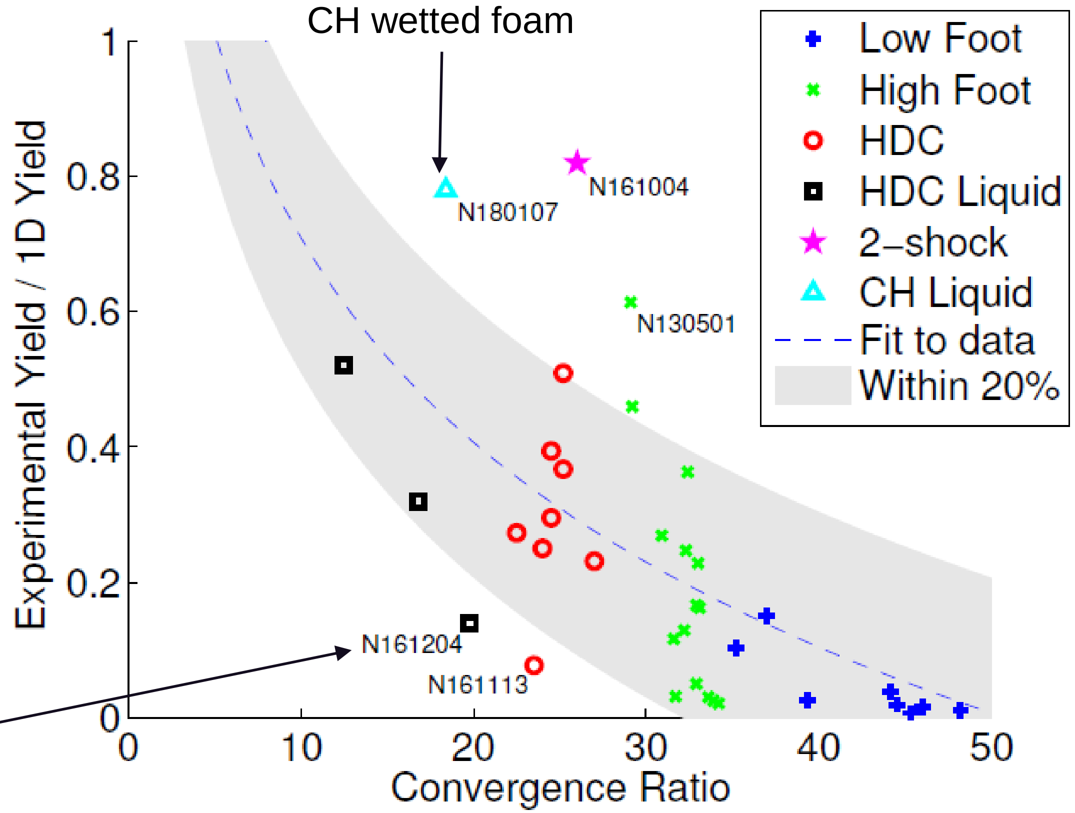

R. E. Olson *et al.* Phys. Rev. Lett. 117, 245001 (2016)
A. B. Zylstra *et al.* Physics of Plasmas 25 056304 (2018)

Convergence adjusted through changes only to target fielding temperature

# A comprehensive look at ICF DT layered implosion data shows performance degradation with respect to convergence

- 1D simulations quantify idealized capsule performance with no impact of asymmetries
- Convergence ratio is one important factor impacting implosion stability



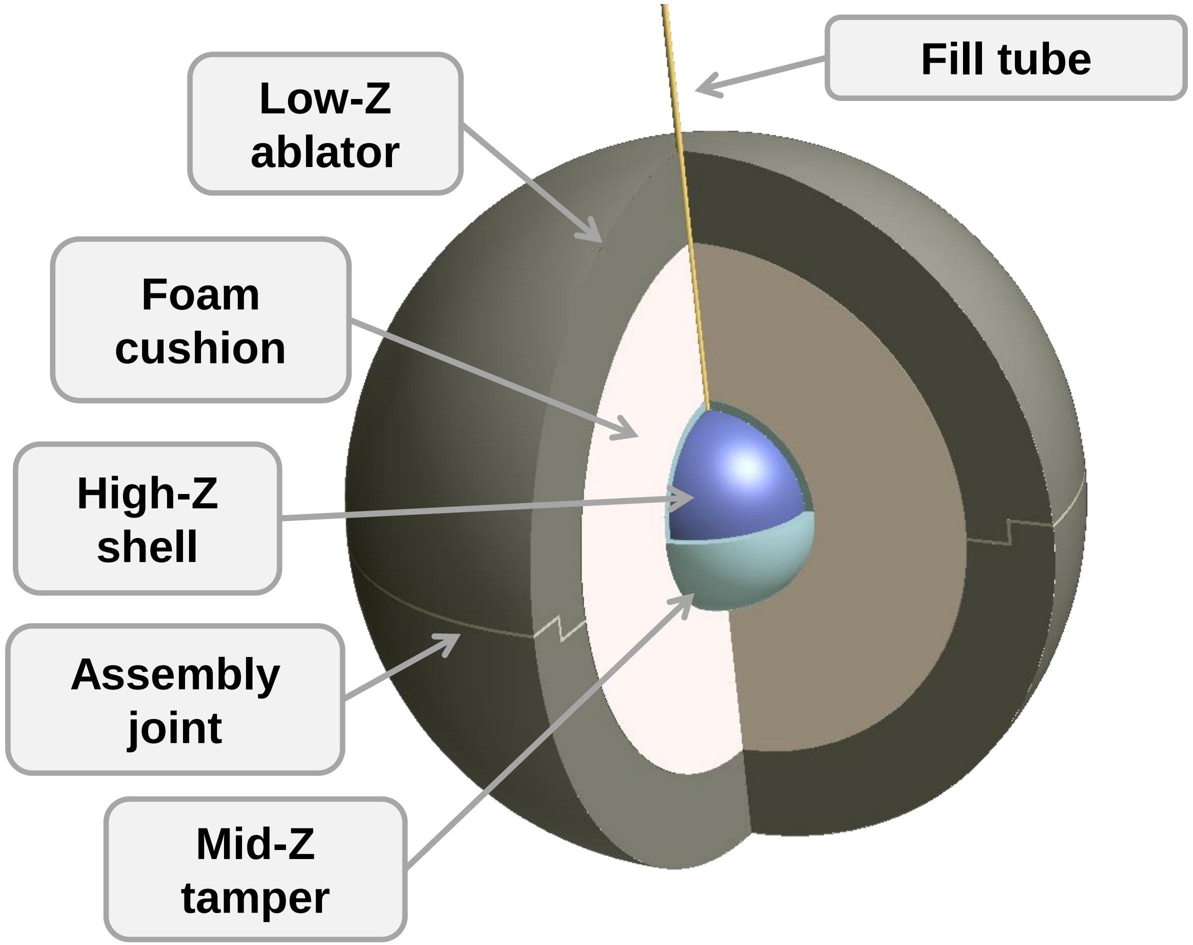

Thanks to S. MacLaren & P. Patel for ice layer data

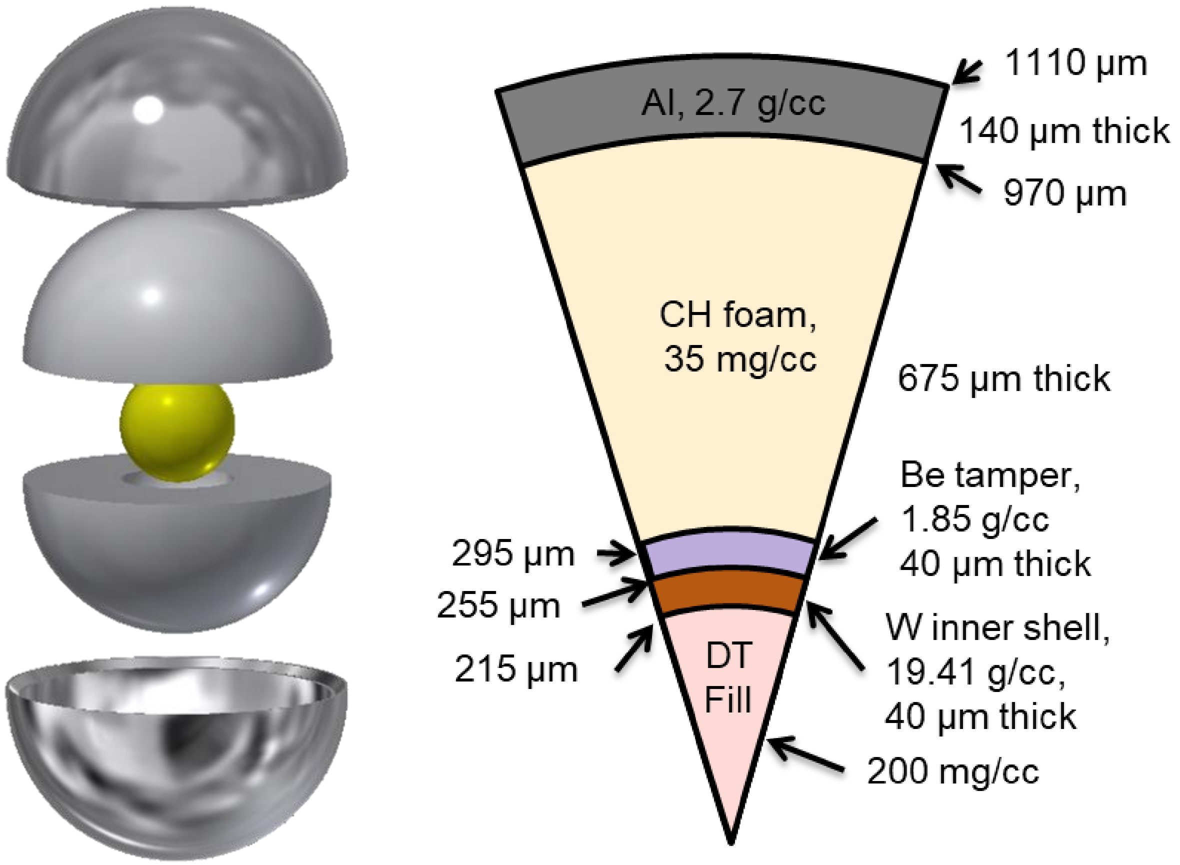
Low Foot: Landen et al., PoP 18:051002, 2011; High Foot: Park et al., PRL 112:055001, 2014; HDC: Le Pape et al., PRL 2018; HDC Liquid: Zylstra et al., PoP 25:056304, 2018; 2-shock: MacLaren et al., PoP 25:056311, 2018; CH Liquid: Haines et al., submitted, 2018

**B. Haines, et al submitted to PoP (2018)**

**Convergence amplifies perturbations!**

# Double-Shells provide a low fuel convergence implosion option

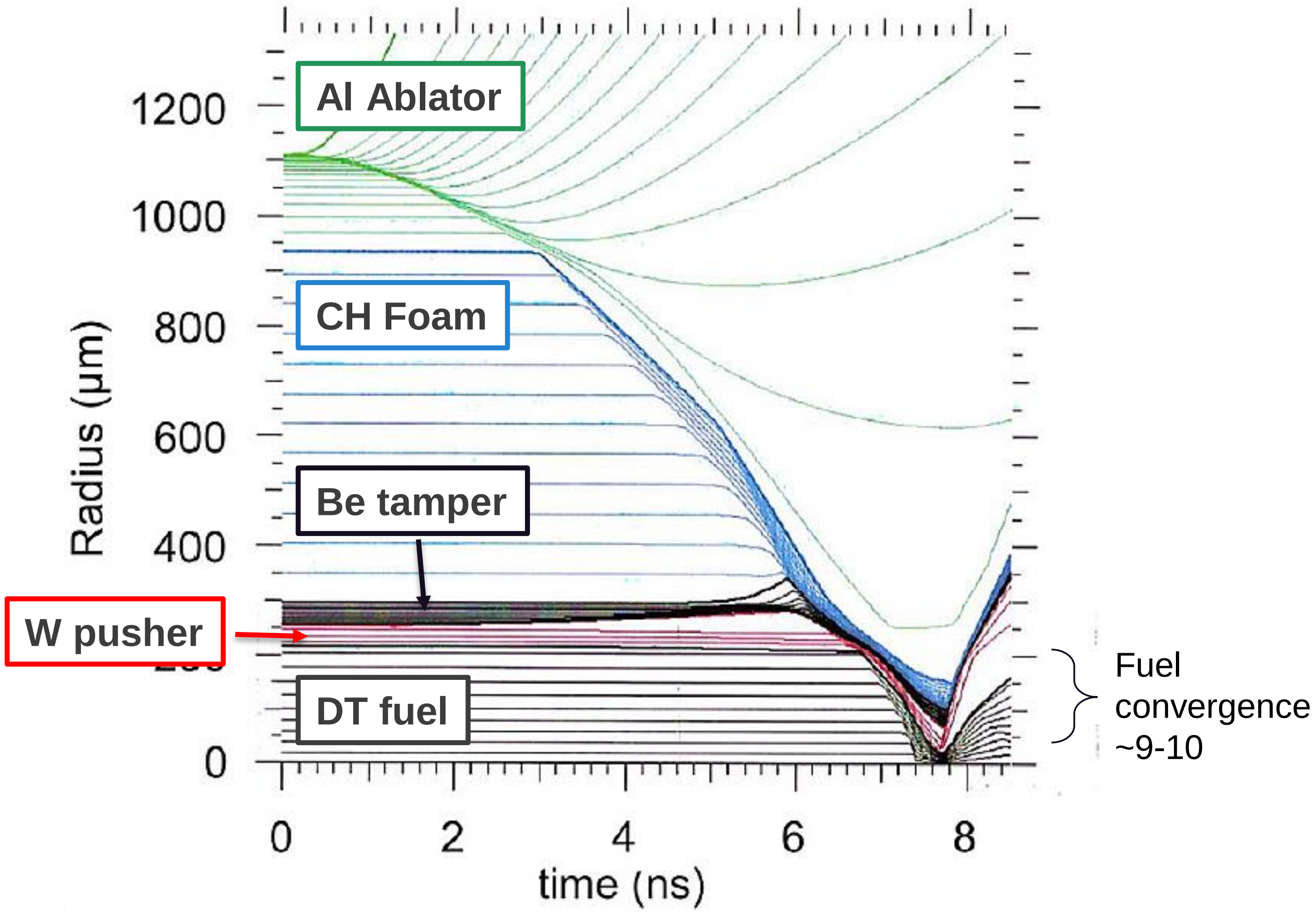



**The Double-Shell capsule design trades "convergence" for engineering**

Montgomery *et al.*, *Phys. Plasmas* (2018)

# Can we characterize Double-Shells well enough to inform our mix and burn models for ICF implosions?




- High-Z pusher (inner shell) has higher initial $\rho R$, so it need less compression to achieve necessary kinetic energy $\frac{1}{2}\rho v^2$
- This leads to several benefits of a high-z pusher:
  - *Lower fuel convergence/compression*
  - *Radiation Trapping*
  - *Reduced Implosion speed*
  - *Lower Ignition temperature*
- Trade-off is engineering challenges
- Open question is whether or not the inner shell converge is not affected by outer shell parameters

**The Double-Shell capsule design is an alternative and complimentary approach to reaching burn**



Montgomery *et al.*, *Phys. Plasmas* (2018)

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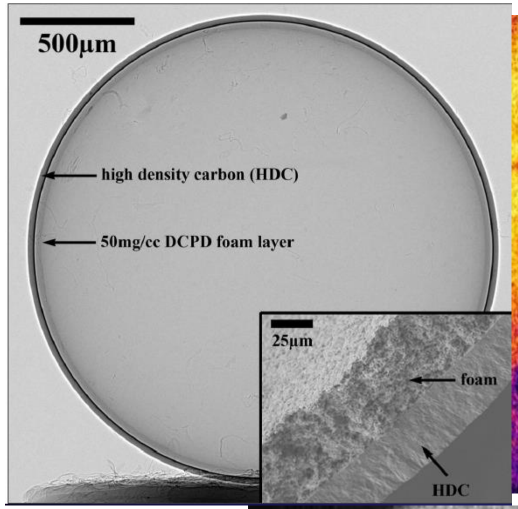
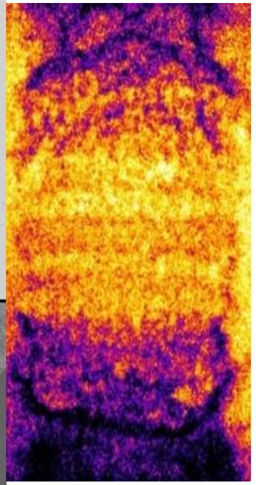
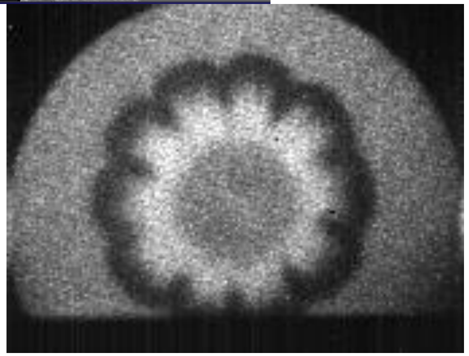
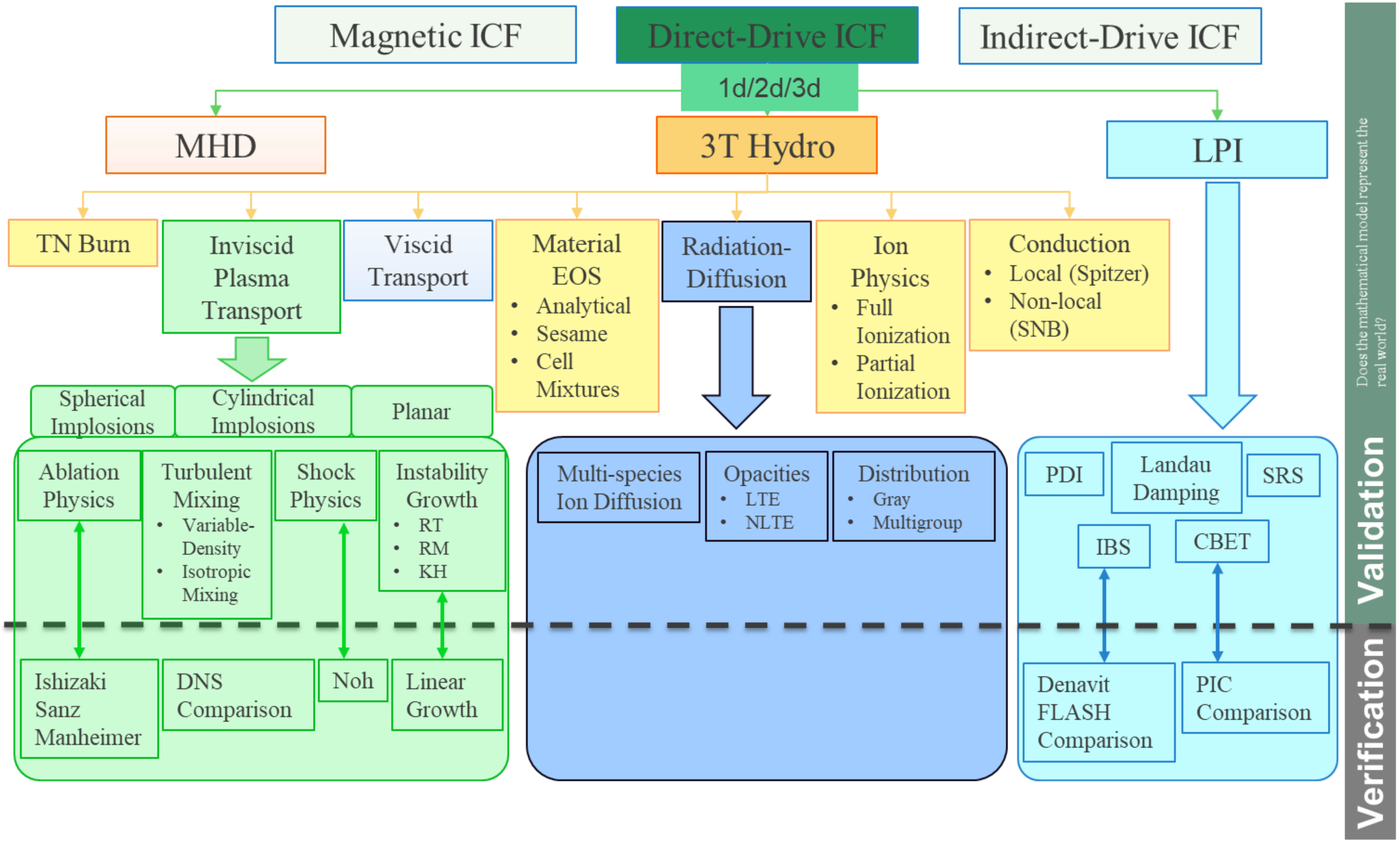


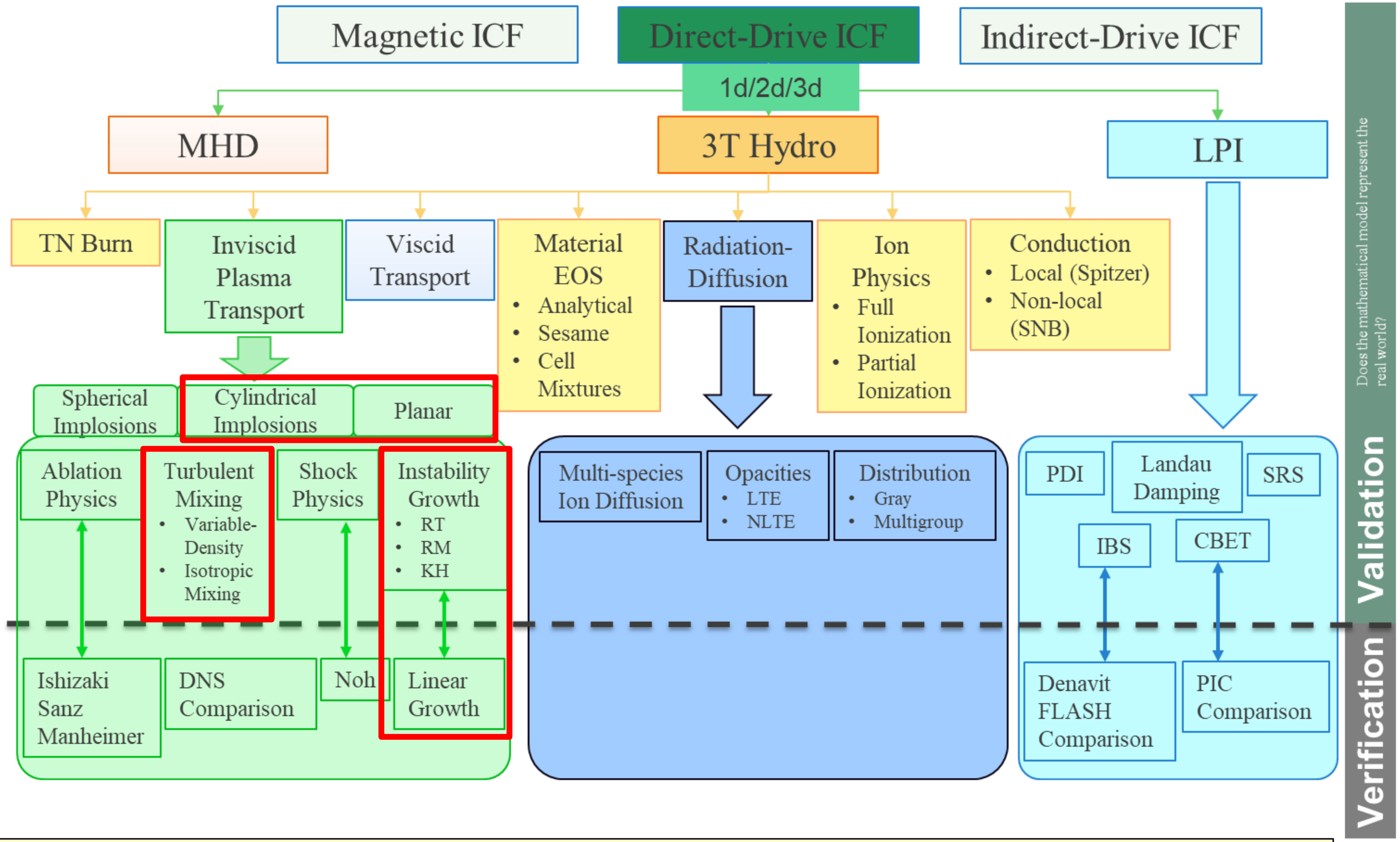





# The simulations codes have a complex interplay of physics models



# Our mix and burn experiments are designed to validate models in our codes




**Validation requires a suite of data covering a range of conditions**

# Our HEDP experiments are focused on validating the LANL four equation turbulent mix model BHR used in our ICF simulations

**k** **Turbulent kinetic energy**

$$\frac{D\rho k}{Dt} = a_i \frac{\partial P}{\partial x_i} - \boxed{R_{ij}\frac{\partial u_i}{\partial x_j} - \rho \frac{k^{3/2}}{s}} + \text{diffusion}$$

**s** **Turbulence scale**

$$\frac{D\rho s}{Dt} = \frac{s}{k}\left[\left(\frac{3}{2} - c_4\right) a_i \frac{\partial P}{\partial x_i} - \boxed{\left(\frac{3}{2} - c_1\right) R_{ij}\frac{\partial u_i}{\partial x_j}}\right]$$

$$\boxed{-c_3 \rho s \frac{\partial u_i}{\partial x_i}} - \left(\frac{3}{2} - c_2\right)\rho k^{1/2} + \text{diffusion}$$

**a** **Mass flux**

$$\frac{D\rho a_i}{Dt} = \boxed{b\frac{\partial P}{\partial x_i}} - \frac{R_{ij}}{\rho}\frac{\partial \rho}{\partial x_j} - c_a \rho a_i \frac{k^{1/2}}{s} + \text{diffusion}$$

**b** **Mixedness**

$$\frac{D\rho b}{Dt} = 2\rho a_i \frac{\partial b}{\partial x_i} - \boxed{2(b+1)a_i\frac{\partial \rho}{\partial x_i} - c_b \rho b \frac{k^{1/2}}{s}} + \text{diffusion}$$

Relevant Terms and Coefficients

- **Reshock**
- **Shear**
- **Compression**

# A focus of our HED hydro-instability program is to test the BHR mix model by examining its performance in the HED regime

*Academia → 1970s for fluid flows*

*National labs*

**2 Eqn model (energy + scale)**

**Multiple species inclusion**

Turbulence scale

Mass flux

Turbulent KE

Mixedness

$$\boldsymbol{k - s - a - b}$$

*BHR initialization parameters*

$$k_0 - s_0$$

Modal model

Experiment initial conditions/profiles

*initialization parameters*

*Instability type*

KH RT RM

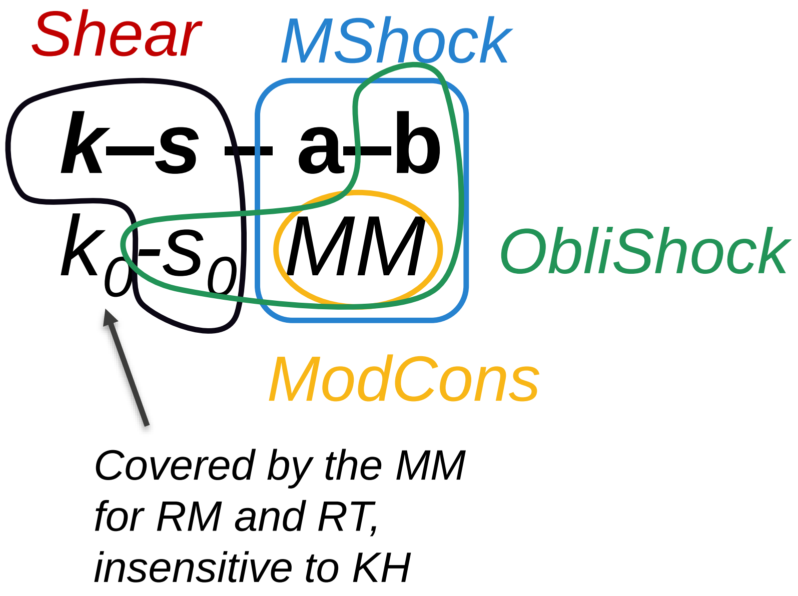
**Experiment input → Model input (predictive)**

**Tuning**

**Experiment output → Model input (not predictive)**

# Our suite of HED hydro-instability projects form a complementary coverage of the parameters of the BHR mix

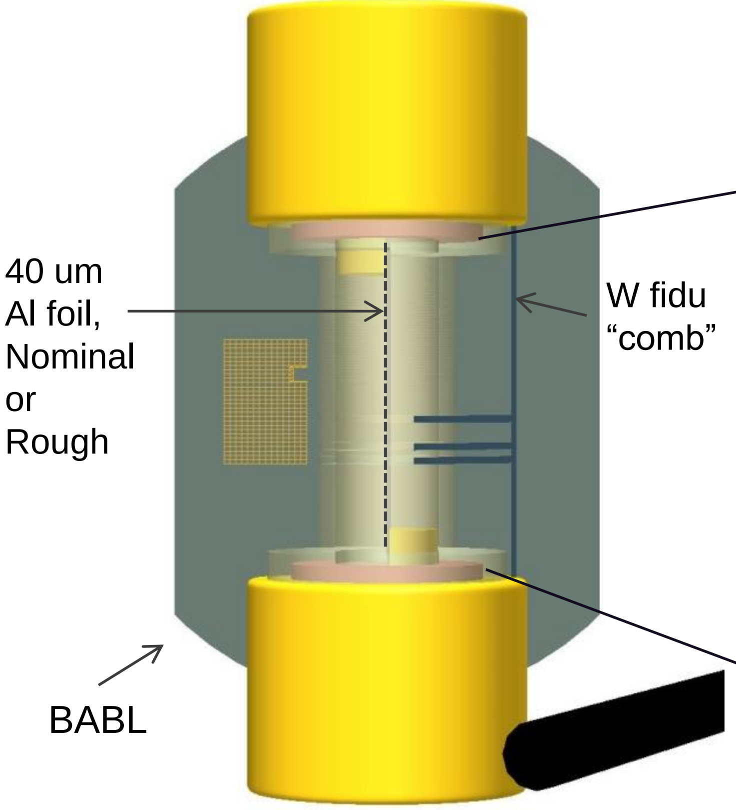
- Counter-propagating Shear (Shear)
  - *Kelvin-Helmholtz (KH) instability*
  - *Atwood numbers*
  - *Surface perturbations*
- Multi-Shock (Mshock)
  - *Richtmyer-Meshkov (RM) instability*
  - *Thin layer feed-through*
  - *Multi-directional shock effects*
- Modal Initial Conditions (ModCons)
  - *RM and Rayleigh-Taylor (RT) instability*
  - *Early-time evolution*
- Oblique Shock (ObliShock)
  - *Mixed KH & RM & RT*
- Cylinders
  - *Introduces convergence effects on above*



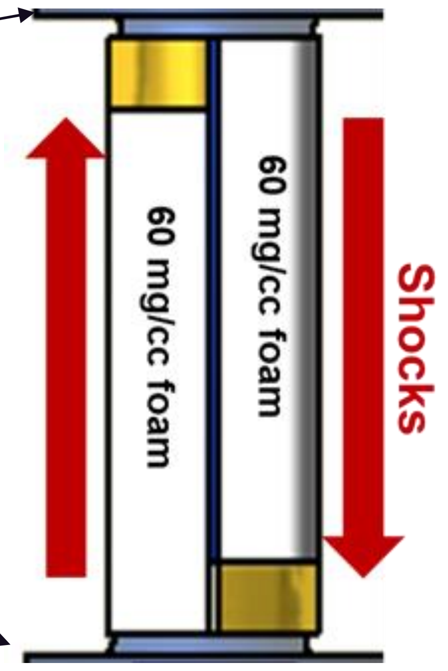
# We have developed a counter-propagating shear platform to investigate multi-mode Kelvin-Helmholtz instabilities and the transition to turbulence

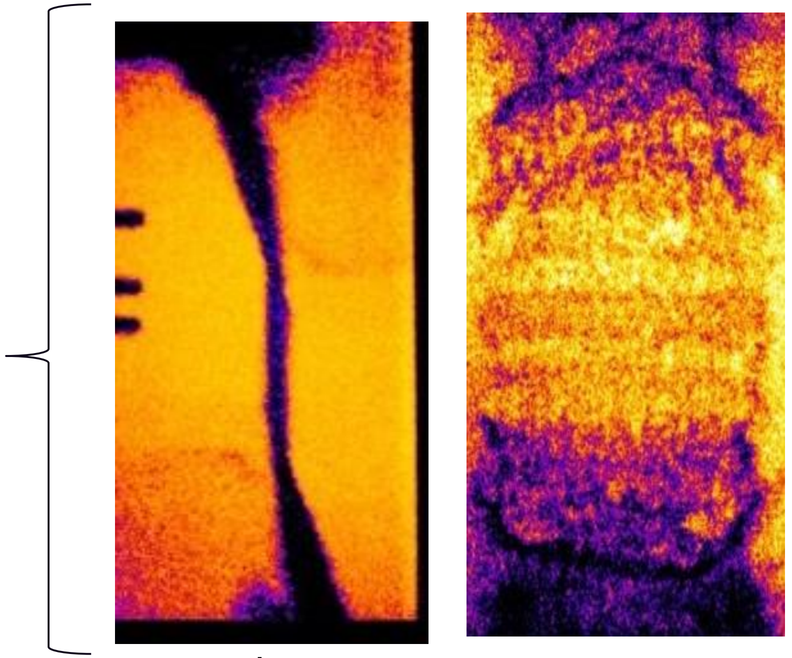
## Radiation driven shock tube platform

The tracer layer is imaged using 130 kJ of laser light onto the BALB foil, producing ~7kJ of x-rays




Edge



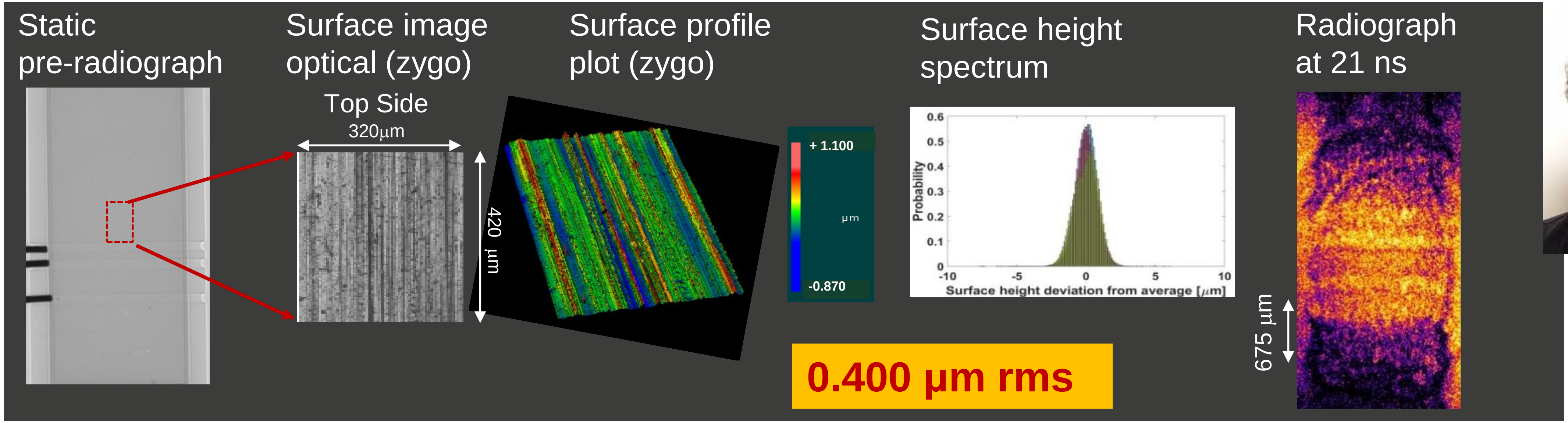



Edge

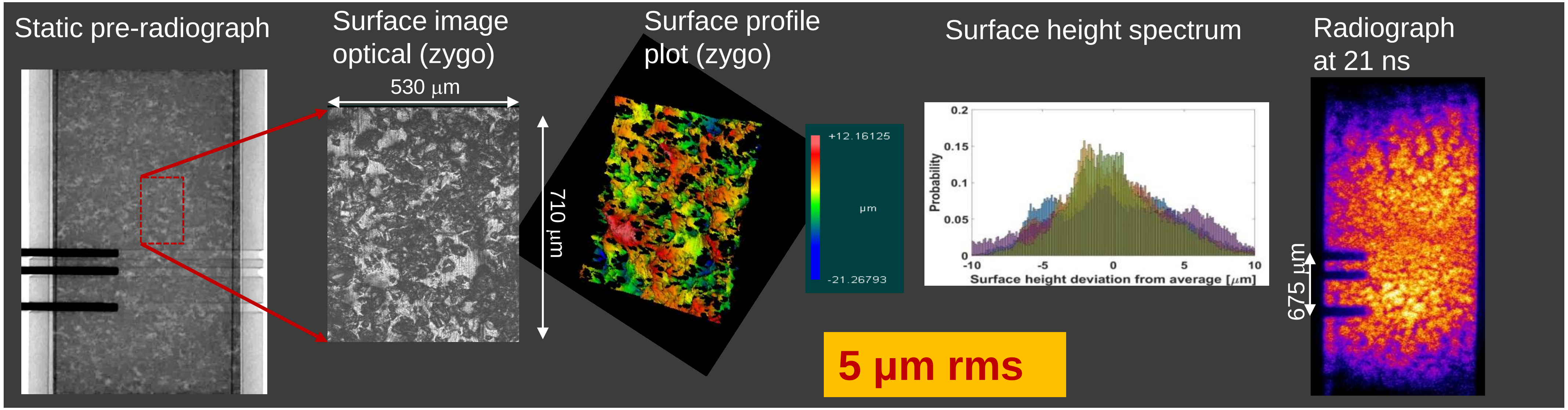
Plan

K. A. Flippo et al. *Rev. Sci. Inst.* **85**, 093501 (2014)

# HED experiments enable control over interface initial conditions not possible in standard low energy density fluid mixing experiments

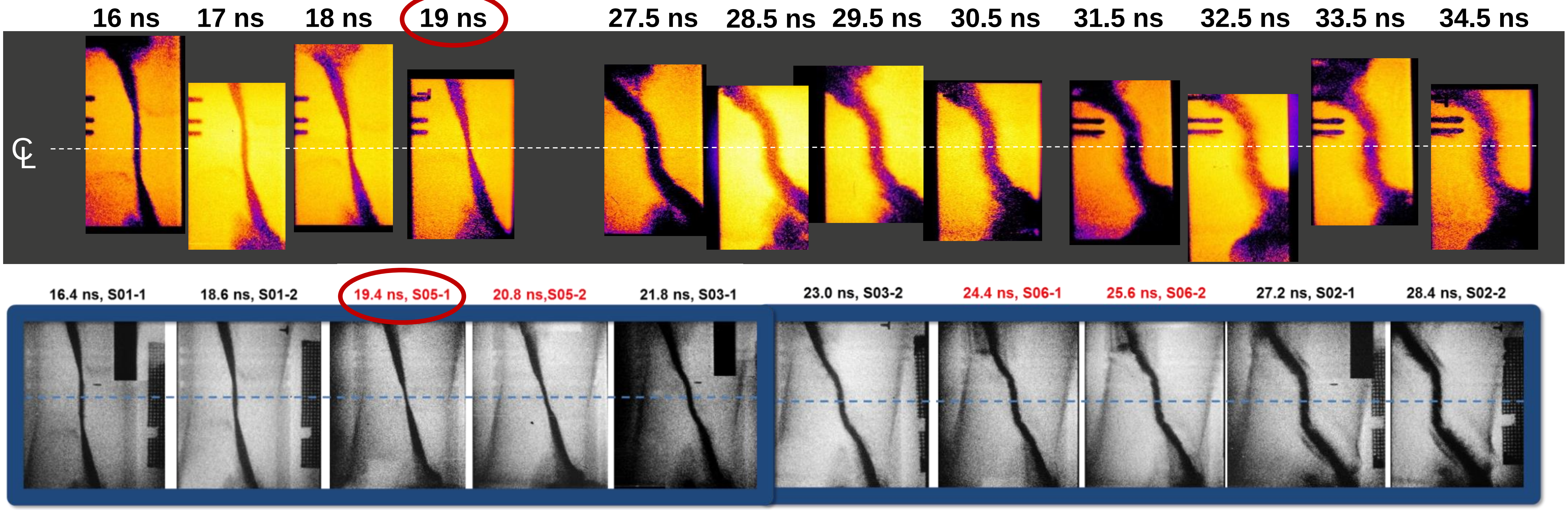



Kirk Flippo
Univ. of
Michigan



# High quality experiments show the effect of initial conditions on the growth of the mixing region

## Roughened Al 40 μm foil




## Nominal Al 40 μm foil

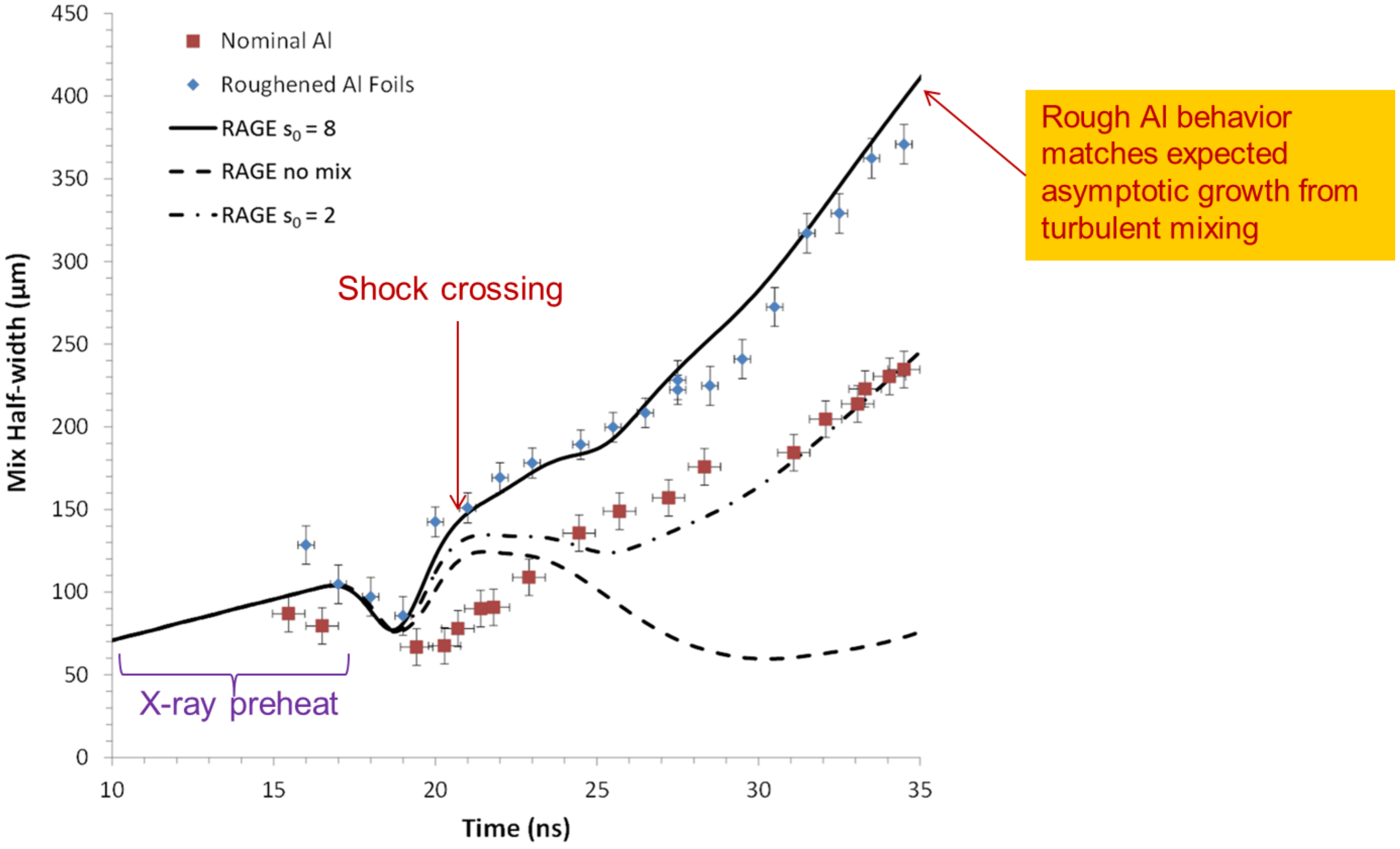
**K. A. Flippo**, F. W. Doss, J. L. Kline, et al. “Late-time mixing sensitivity to initial broadband surface roughness in high-energy-density shear layers,” *Phys. Rev. Lett.* (accepted, in press)

**NIF laser reproducibility enables high quality long data sequences built from multiple shots**

# Experiments show good agreement with simulations with key choices by the designer

There is still work to improve the BHR:

- So typically used as a free variable
- The BHR mix model is turned on during the simulations with designer's best feeling
- We are developing a modal initialization model which would be initialize at the beginning of the simulations

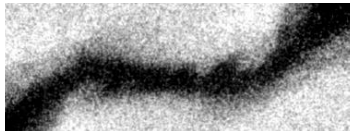


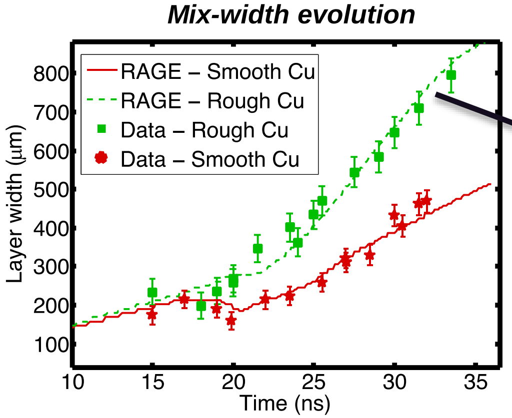

**Comparisons of the mix widths between experiments and simulations while useful is not very constraining for models and more informative**

# The ensemble of radiography data gives a direct comparison between model and experimental turbulent kinetic energy

## Model

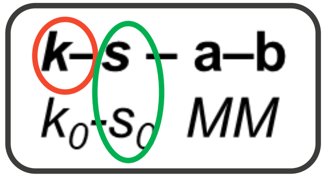
**Measure mix width**
**→ tune $s_0$ → simulate *k***

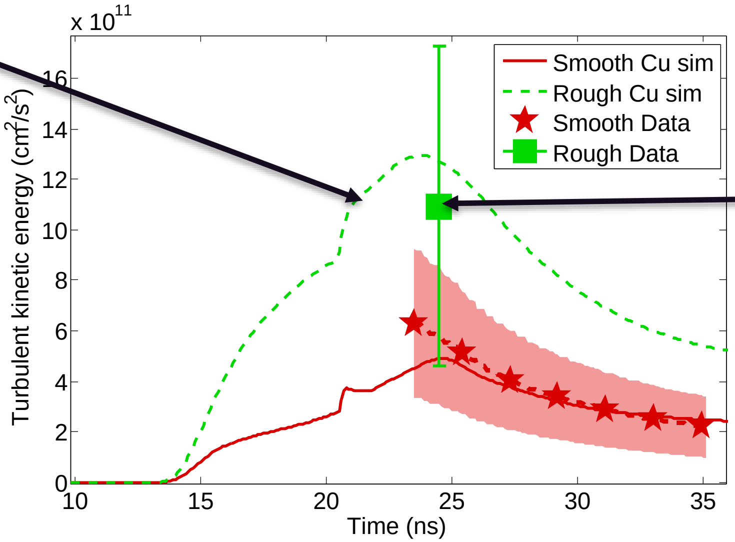





*$s_o$ increases with increasing surface roughness*

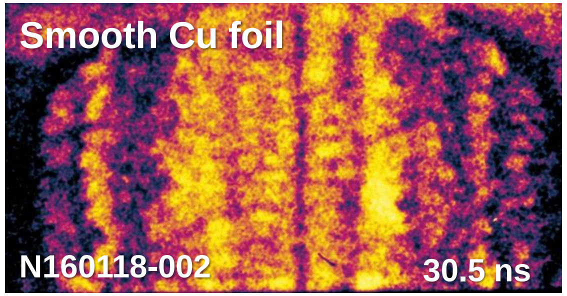
Doss et al,. Submitted to PRE (2018)

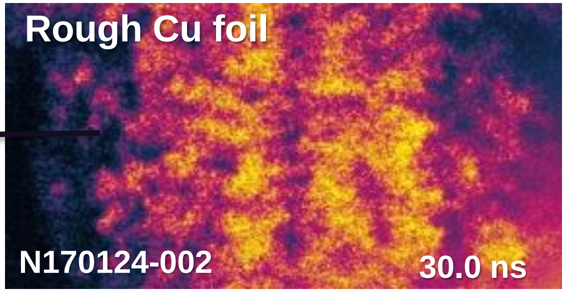



## Analytic

**Measure roller and rib growth**
**→ calculate *k***




Single data point w/ large error bars due to lack of rib evolution
→ *ongoing analysis development*

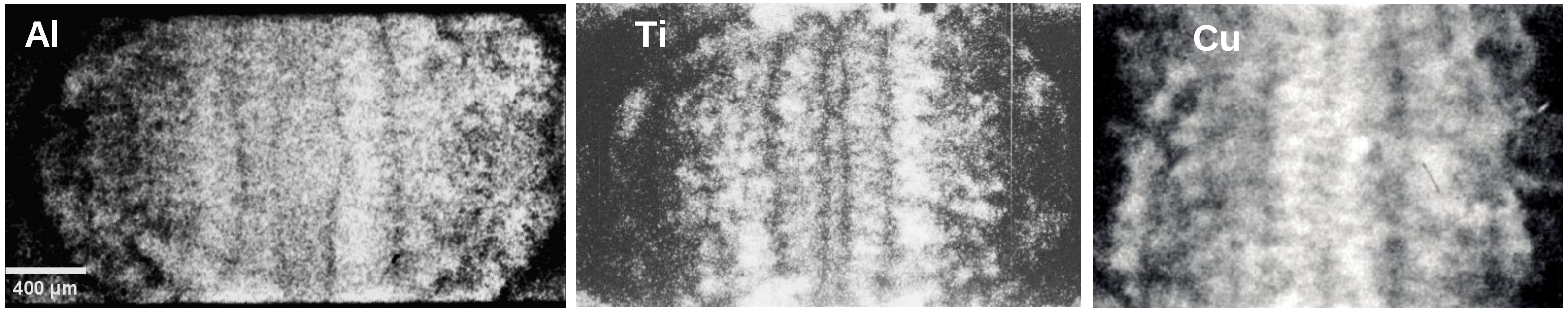
Forrest Doss

**The roller and rib growth rates can be used to calculate the specific turbulent kinetic (kTKE) energy in the system, which is consistent with the RAGE & BHR models**

# Energy ratios in our HED experiment follow root-density Atwood scaling (roughly) from canonical fluid experiments

***Ratios of TKE cancel out systematic modeling uncertainties, making error smaller than it might naively appear***

Papamoshcou & Roshko, *JFM* **197** 453 (1988)
Dimotakis, “Entrainment into a Fully Developed, Two-Dimensional Shear Layer” AIAA-84-0368 (1984)




**TKE (cm/s)$^2$** 1.1e12 ± 6e11 4.5e11 ± 2e11 3e11 ± 6e11

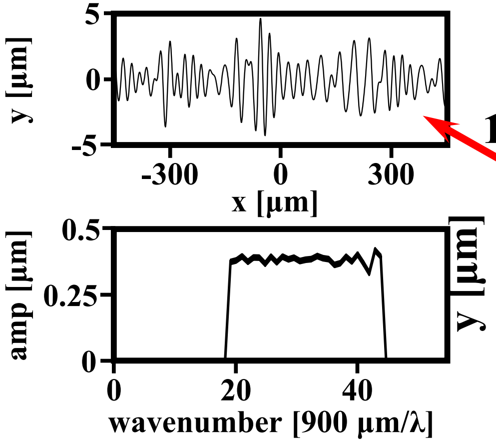
**Al/Ti = 1.5 +- 0.6**
(“should be” 1.3)

**Ti/Cu = 1.73 +- 0.5**
(“should be” 1.4)

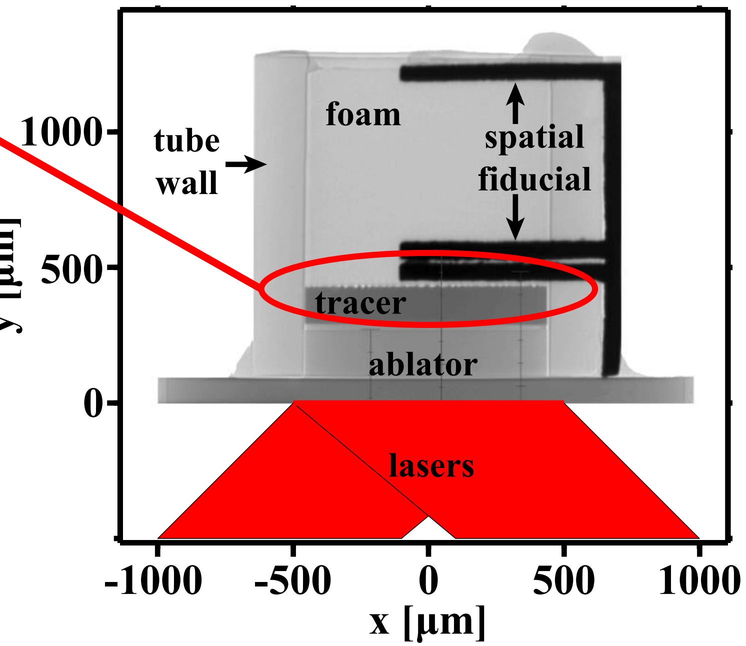
**If our calculated TKE did not follows hydrodynamic scaling laws, that would indicated that our HED experiments were outside the regime of model applicability**

# The modal conditions (ModCon) experiments are designs to validate our modal model used to evolve the mix problem from simulation initiation

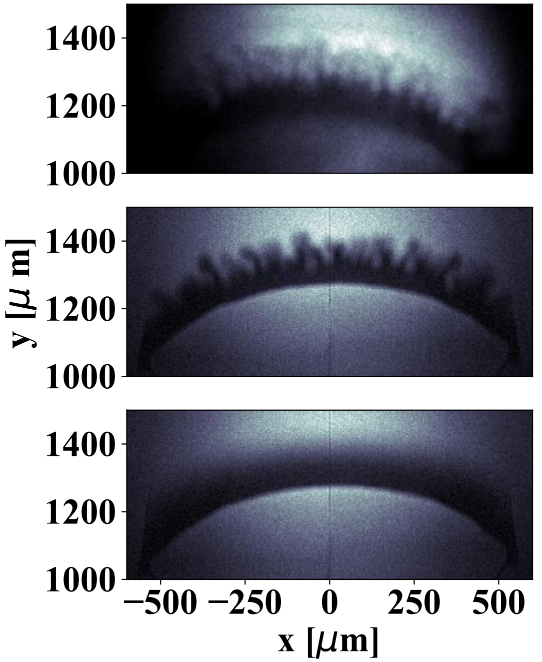
## Initial perturbation



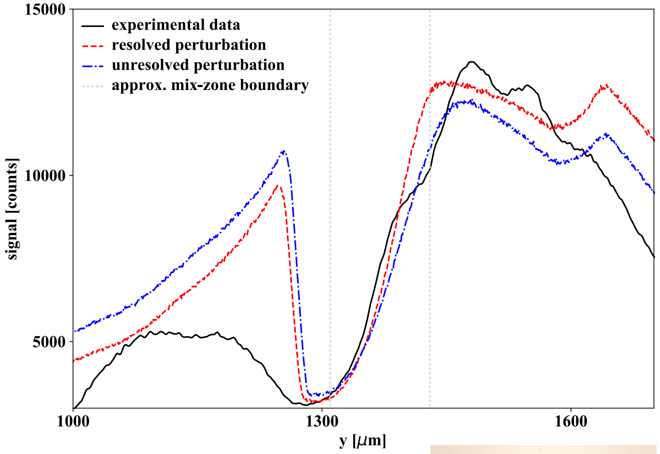

## Pre-shot image




## Experiment and simulation




## Interface width



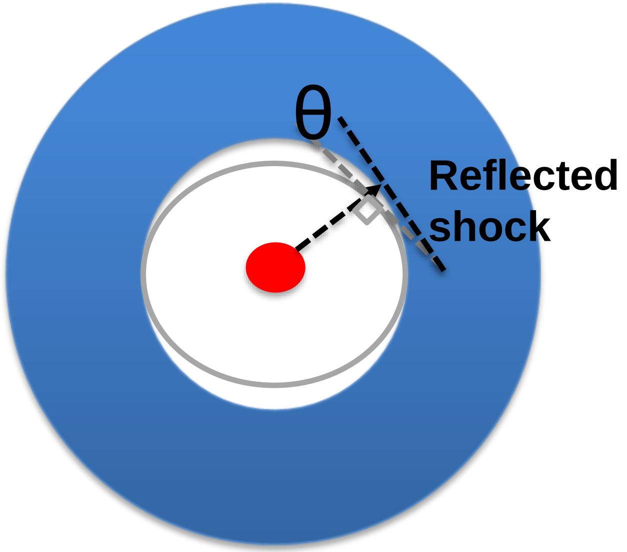

1. C. A. Di Stefano, *et al.* Phys. Plasmas 2017
2. B. Rollin and M. Andrews, *J. Turbulence*, 2013
3. G. Malamud, *et al. HEDP*, 2013

Carlos De Stefano

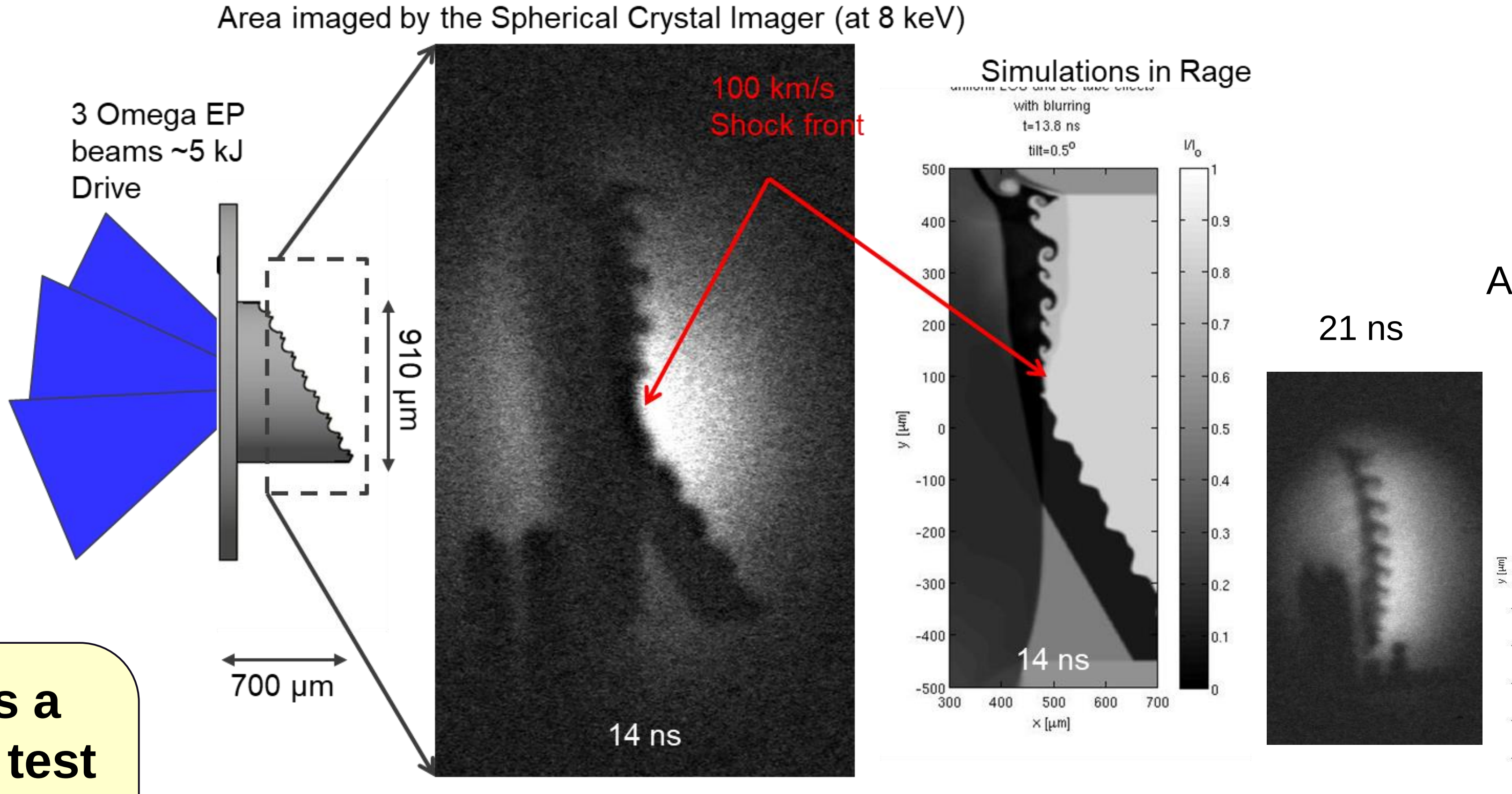
This type of perturbation is relevant to initialization schemes for hydrodynamic mixing (e.g. modal model)[3].

# The Oblique Shock Campaign seeks to understand the interplay between Kelvin-Helmholtz and Rayleigh-Taylor instabilities on mixing in an HED environment

Asymmetric capsule drive can generate oblique shocks at interfaces

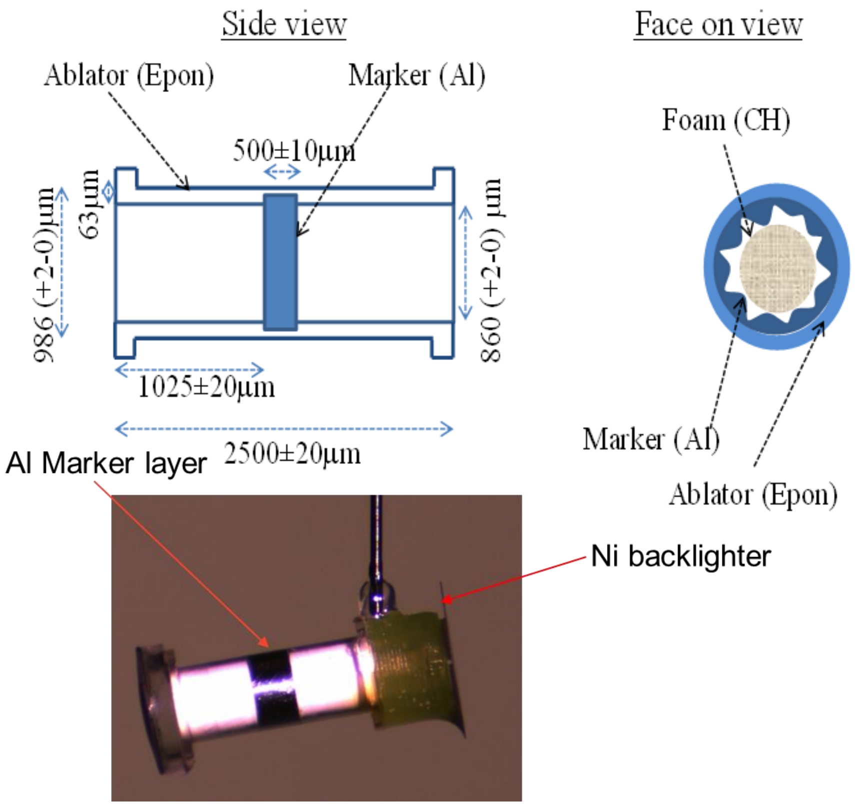


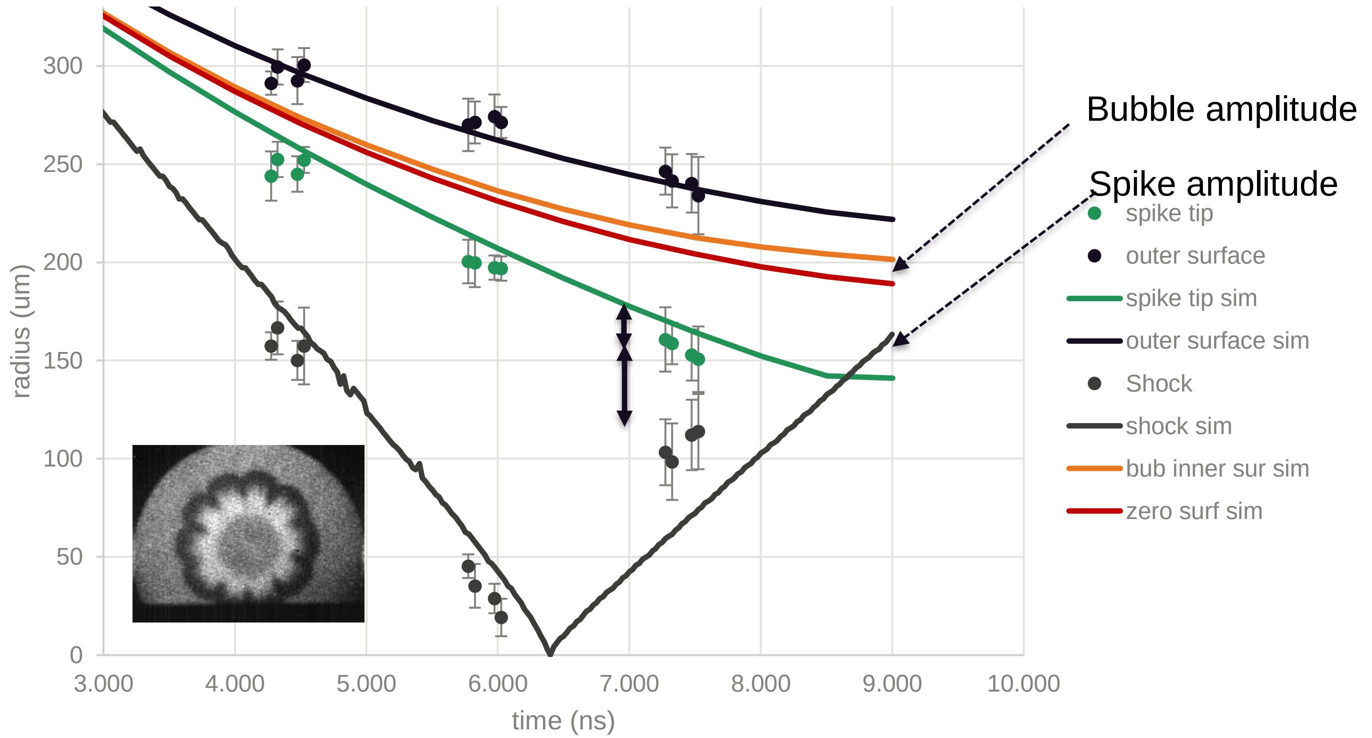

**Oblique shock provides a multi-physics integrated test for our models related to a potential technical issues for ICF implosions**




Alex Rasmus

# We are re-establishing a cylindrical implosion platform to validate our hydrodynamics in convergent geometries

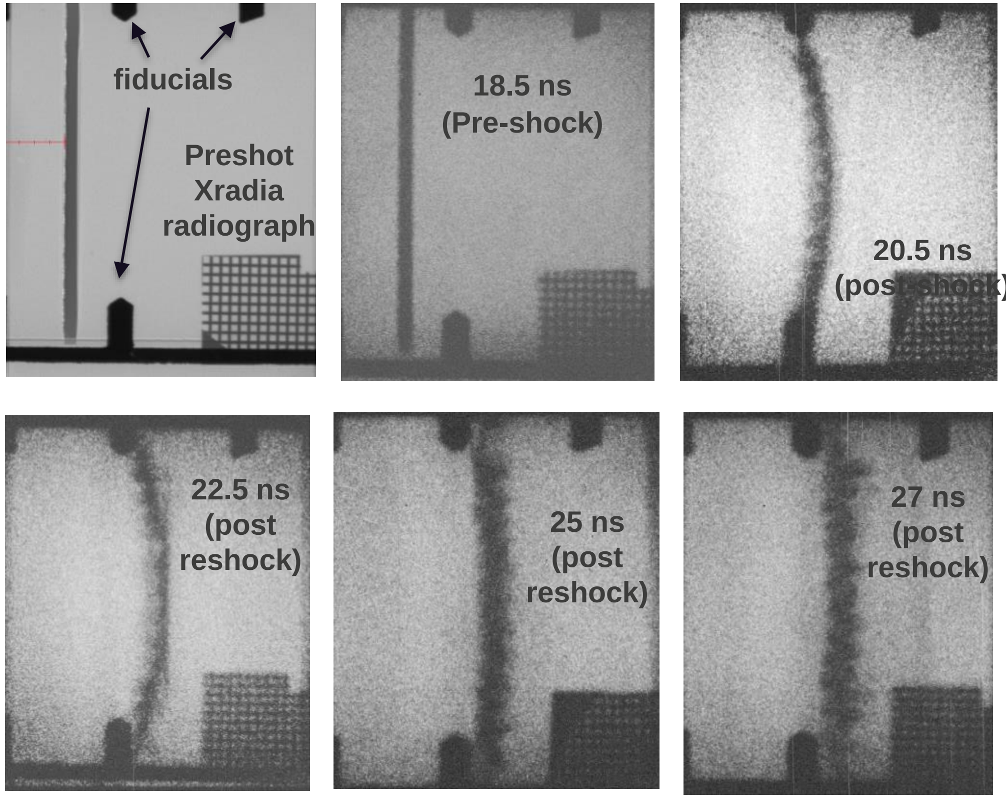


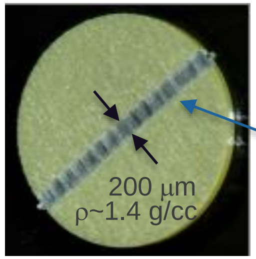

**Cylindrical implosions enable direct diagnostic access to instability growth in convergent geometry. Convergent geometry adds:**

- Compressibility
- Changing wave lengths
- Different Atwood numbers for bubbles an spikes

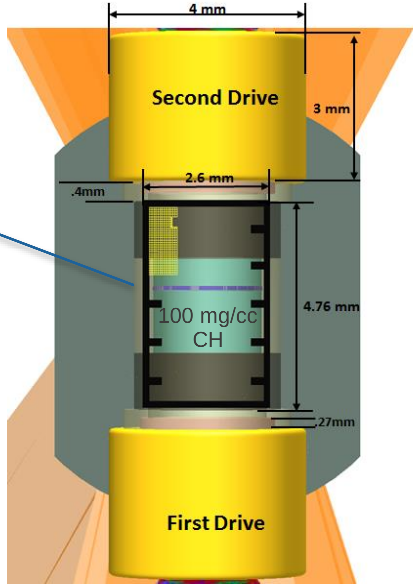
# The MShock Campaign examines RM instability growth with multiple shocks with multiple interfaces




**Radiograph data shows growth of high density layer, and features of the seeded mode**

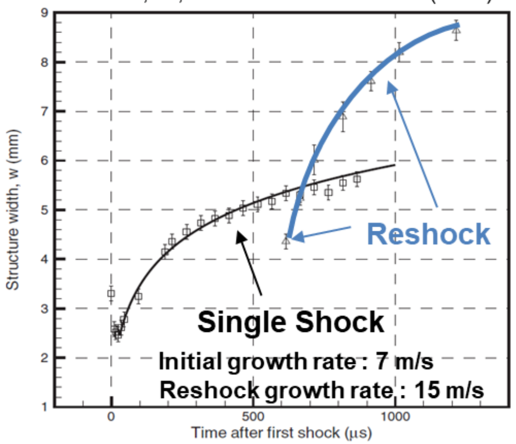



Plastic disk with 80 x 200 μm thick CHI tracer layer



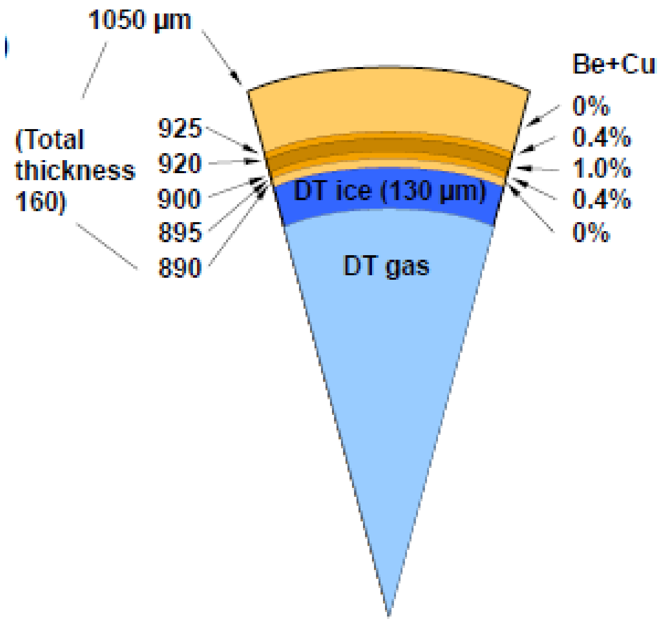

***Fluid Reshock Experiments***

Leinov, E., *et al*. J. Fluid Mech 626 (2009)




**Grades dopant Ignition designs have multiple interfaces near ice layer**

Be HF capsule



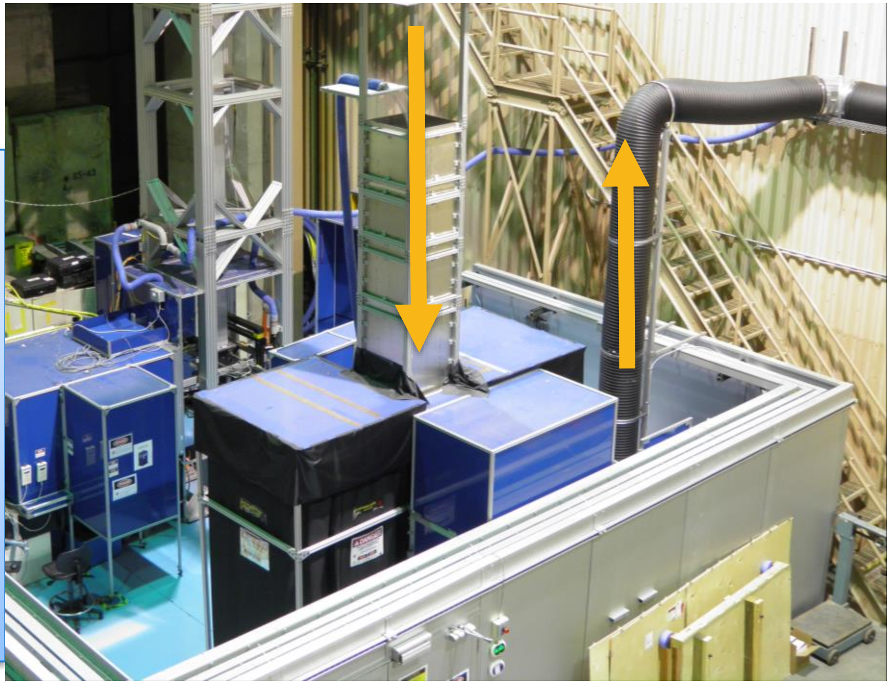

[1] Simakov *et al.* PoP **21**, 022701 (2014).
[2] Yi, *et al.* PoP (2014).

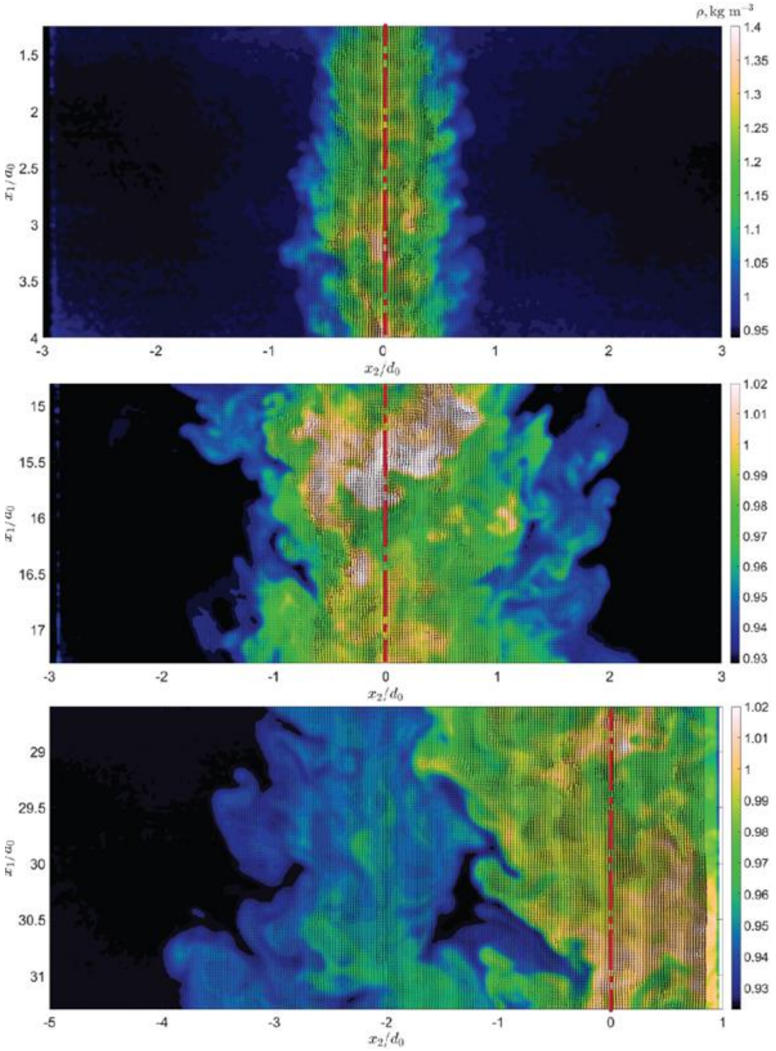
# One advantage to the national lab is working closely with partners working in different regimes on the same problems

Turbulent Mixing Tunnel:
Open-circuit wind tunnel

Measurements:
- 10,000 velocity & density fields of the flow per station

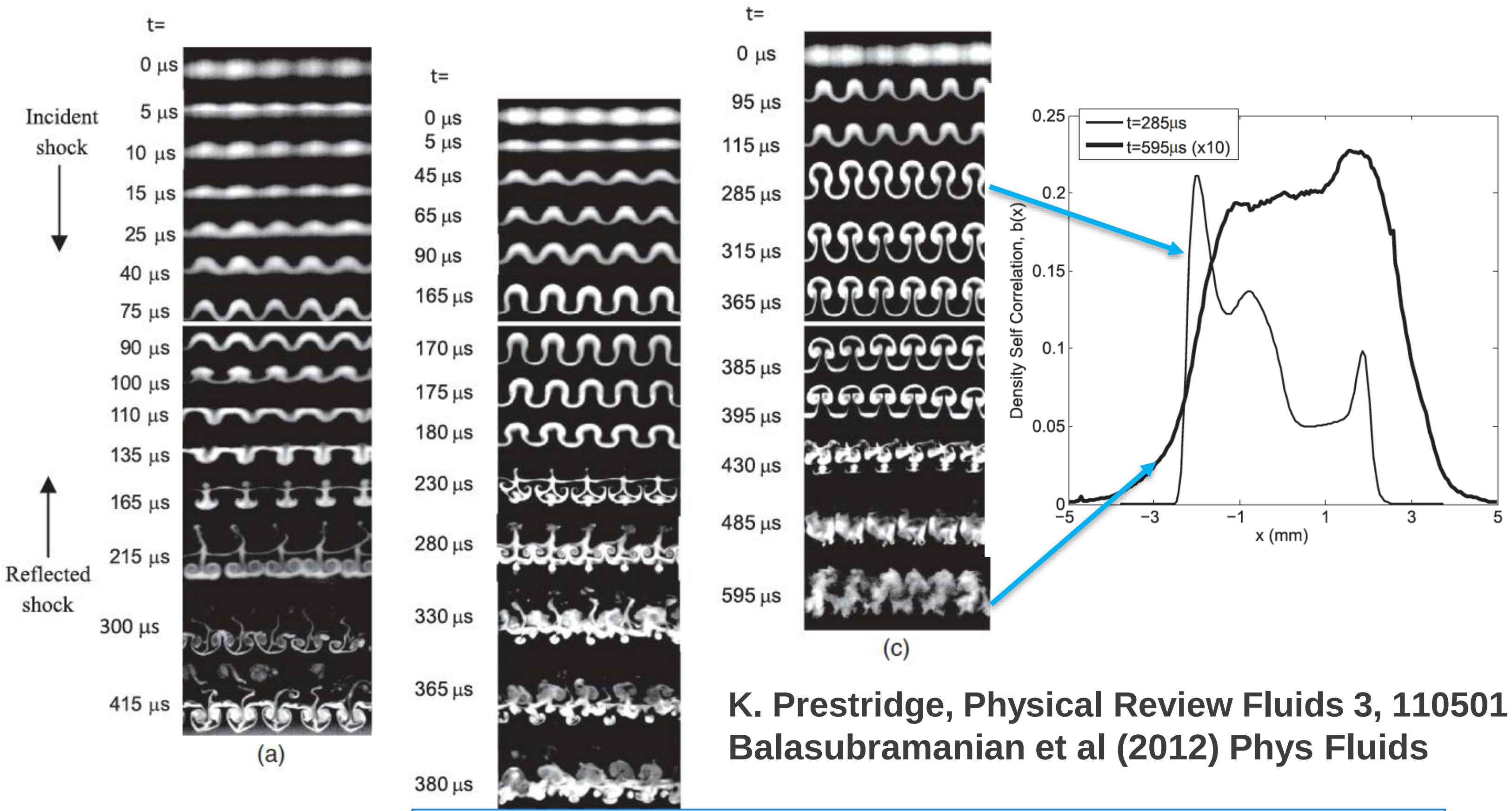
Jet conditions:
*Re* = 20,000
*At* = 0.1, 0.6
*M* = .09, .02



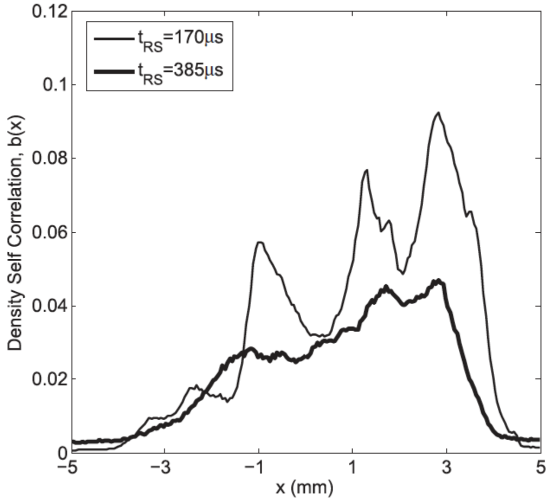



EXTREME FLUIDS
extremefluids.lanl.gov

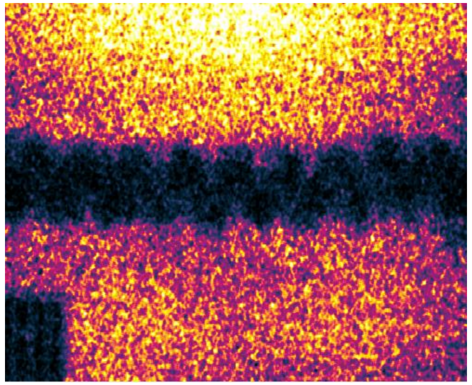
# Mshock platform is duplicating gas curtain experiments in different flow conditions




*Later reshock results in enhanced mixing*




**K. Prestridge, Physical Review Fluids 3, 110501 (2018)**
**Balasubramanian et al (2012) Phys Fluids**



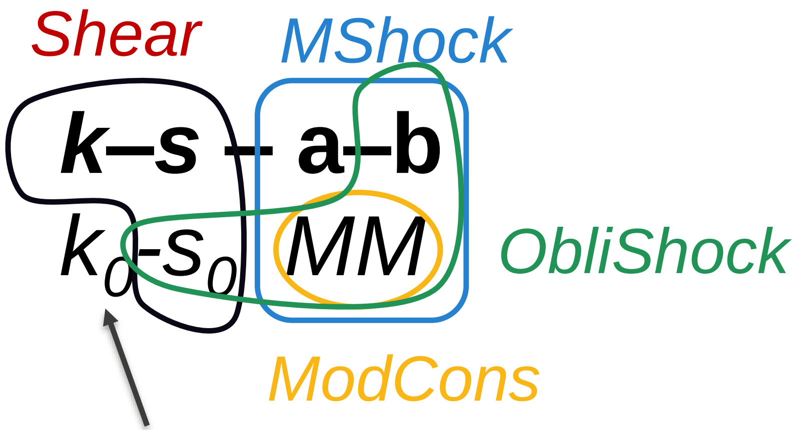
EXTREME FLUIDS

extremefluids.lanl.gov

**Mshock is an extension of fluid experiments and should be able to detect similar features in *b***

# Our suite of HED hydro-instability projects form a complementary coverage of the parameters of the BHR mix model

- Counter-propagating Shear (Shear)
  - *Kelvin-Helmholtz (KH) instability*
  - *Atwood numbers*
  - *Surface perturbations*
- Multi-Shock (Mshock)
  - *Richtmyer-Meshkov (RM) instability*
  - *Thin layer feed-through*
  - *Multi-directional shock effects*
- Modal Initial Conditions (ModCons)
  - *RM and Rayleigh-Taylor (RT) instability*
  - *Early-time evolution*
- Oblique Shock (ObliShock)
  - *Mixed KH & RM & RT*
- Cylinders
  - *Introduces convergence effects on above*




*Covered by the MM for RM and RT, insensitive to KH*

# We are developing models that utilize the BHR mix model to advance mix morphology in terms of a distribution function to modify reactivity

**Simulations: fusion burn is modeled through a reaction rated equation which can be modified by mix**

$$\dot{N}_{DT} = \frac{N_D N_T}{V} \langle \sigma v \rangle (T_i)$$

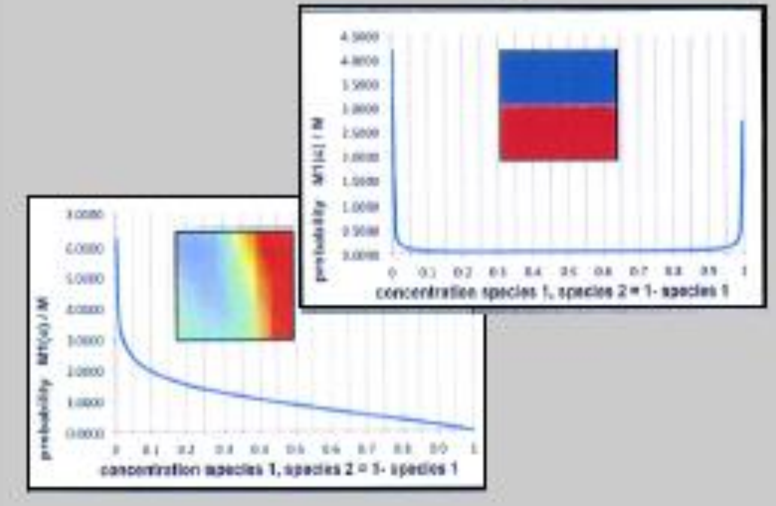

Limiting cases of mixed cell

t>0


Unresolved cell structure that might be computed from DNS

Beta Probability Distribution Function

$$p(c) = \frac{c^{\alpha-1}(1-c)^{\beta-1}}{B(\alpha,\beta)}, \quad B(\alpha,\beta) = \int_0^1 dc\, c^{\alpha-1}(1-c)^{\beta-1}$$




- BHR: time evolution and distribution of mix based on Reynold's Averaged Navier-Stokes (RANS) Equations
- Flow decomposed into average and fluctuating components
- Ensemble averaged equations provides mean motion of flow
- PDF: physical representation of unresolved cell morphology

BHR: concentration c, and density self correlation b

→ PDF: p(c), fraction of cell (by mass) at concentration c

→ Reaction Rate equation

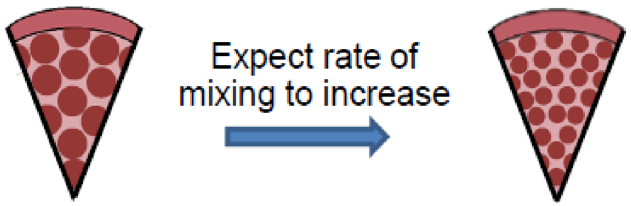
Burn and mix are interdependent, experiments to test fidelity of approach cannot separate the two

reference

# We have developed experiments that attempt to control the mix morphology

- Measured yields are indicative of how well the D and T species atomically mix
- How fast D and T components mix depends on the initial pore size, distribution, foam density and gas pressure

Typical separated reactants mix experiment



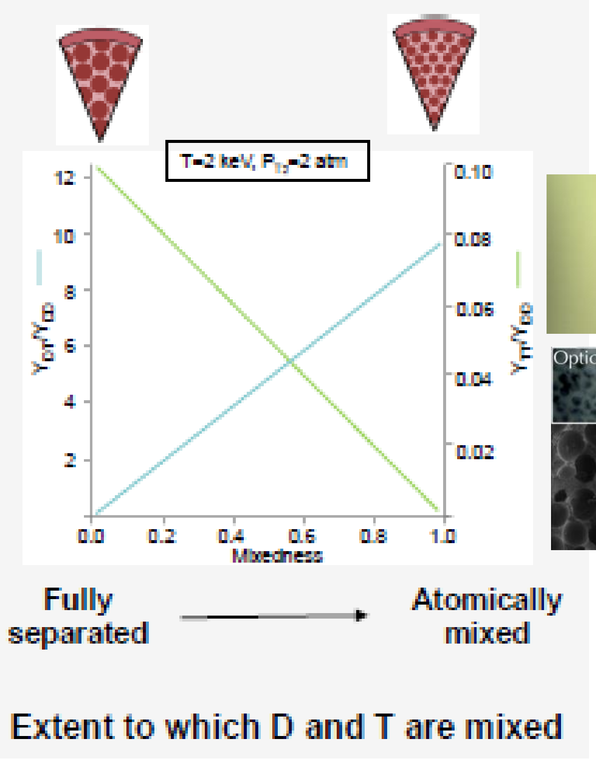

- Initial pore sizes estimated at ~ 100 μm

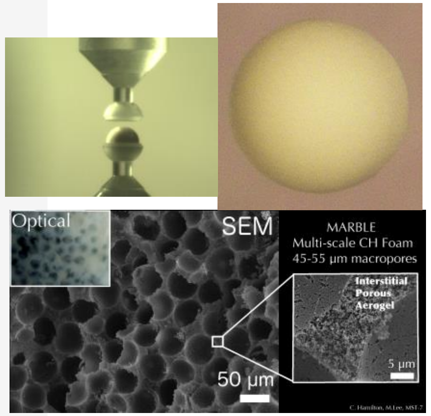
  *Based on assumption of shock-driven variable density isotropic turbulent decay*

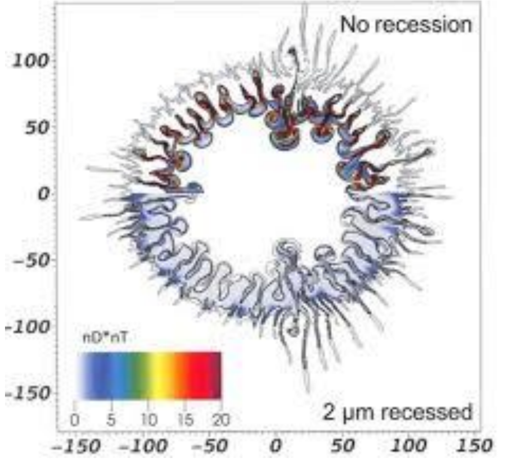
- Key measurement: yield ratio

  *Eliminates need to know detailed information on ion temperature*

- Multi-D simulations incorporating a foam model indicated differences in DT yield will be observed




J. Pino et al, PRL (2015)

# A principle focus of LANL HEDP program is mix and burning plasmas to validate models for ICF implosions

**This is accomplished using three threads:**

- **Novel implosion platforms to inform performance**
  - Reduced convergence wetted foam targets
  - Double Shell targets
- **Focused experiments for validation**
  - Hydrodynamic mix
    - *Shear driven hydrodynamic instabilities*
    - *Mod Con*
    - *Oblique shock*
    - *Cylinder*
  - Burn model
    - **PDF burn model**
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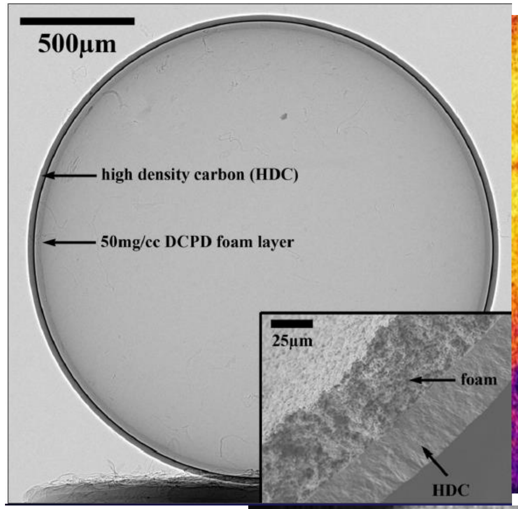
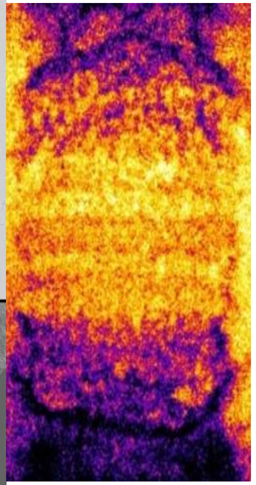
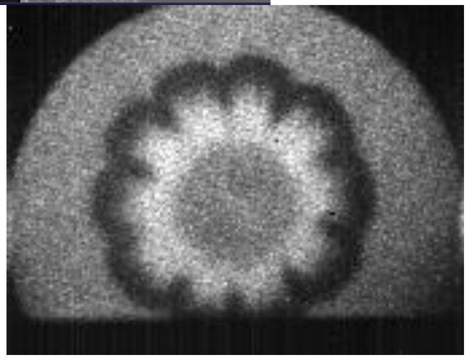
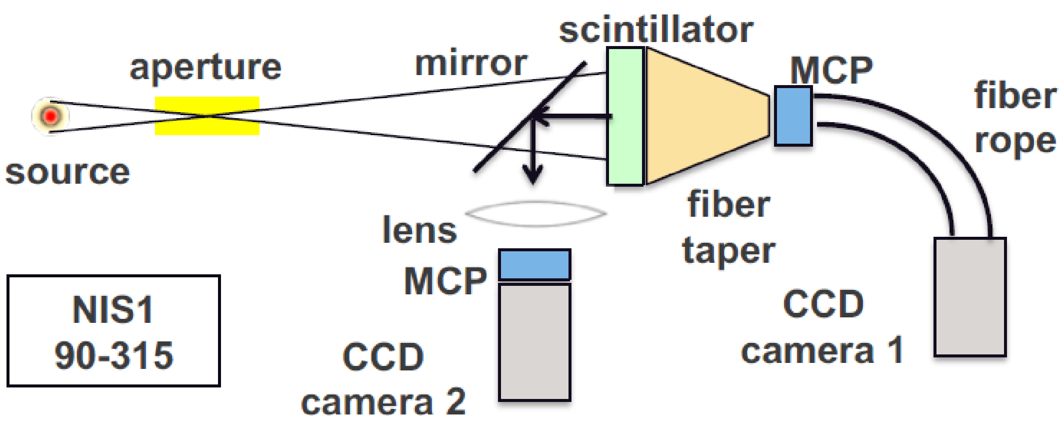
    - **Kinetic Plasma Effects**
- **Burning Plasma Diagnostics**
  - Neutron imaging, Reaction History, Radio-Chemistry
- **Developing UQ tools**
  - Bayesian Inference Engine

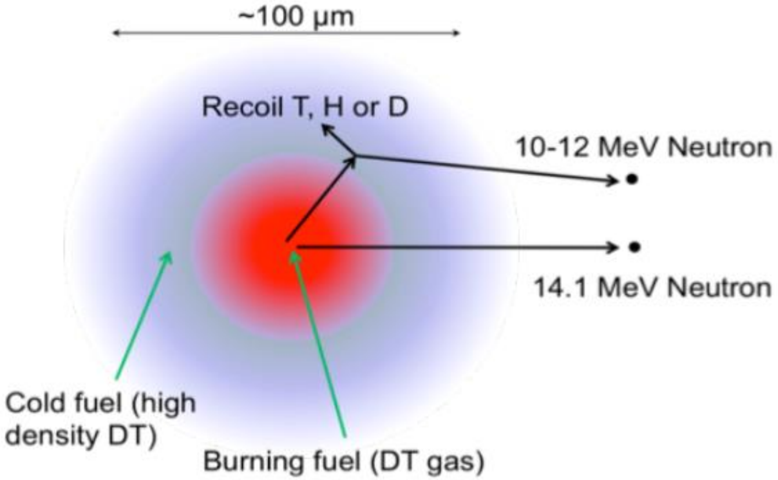


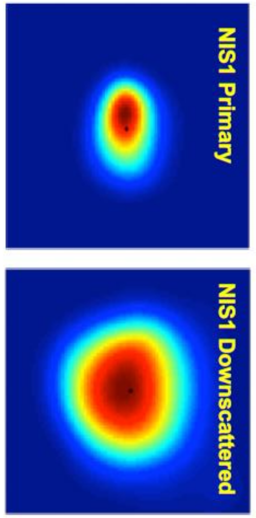



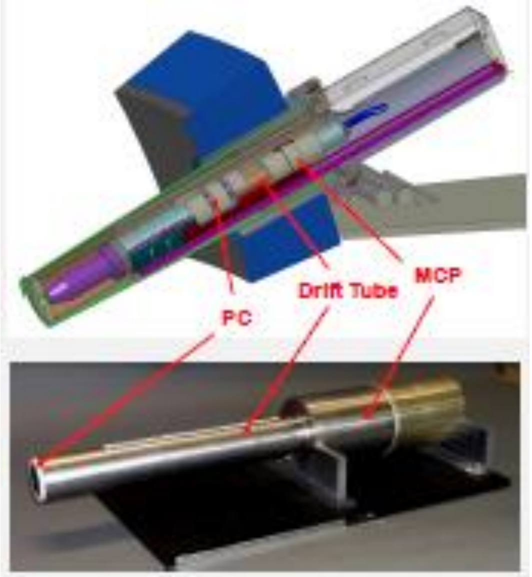


# Investigating burning plasmas requires high quality nuclear diagnostics

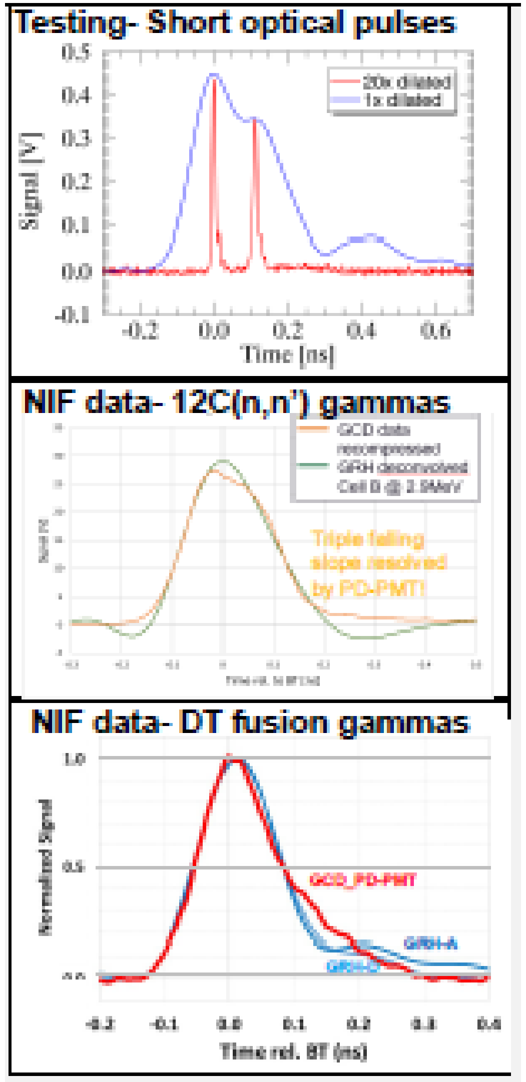


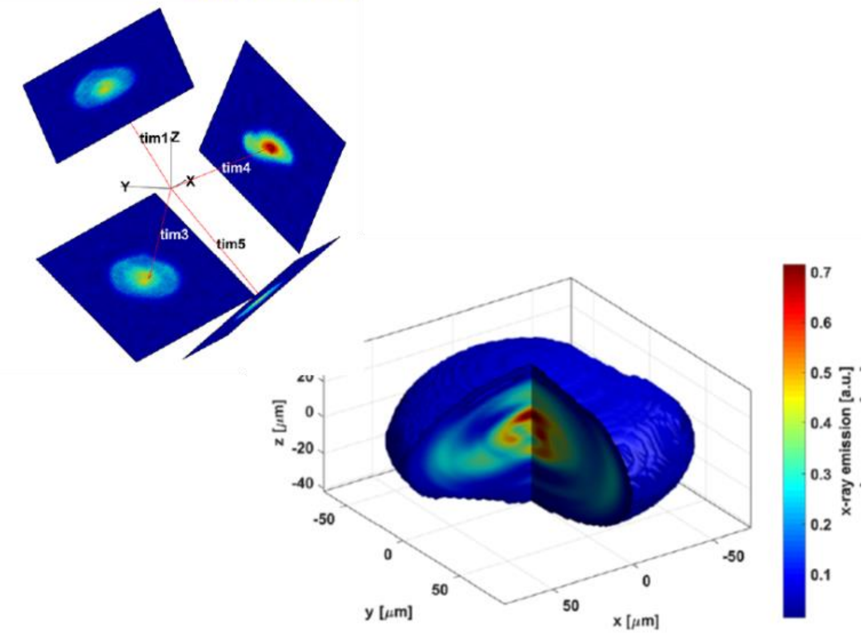





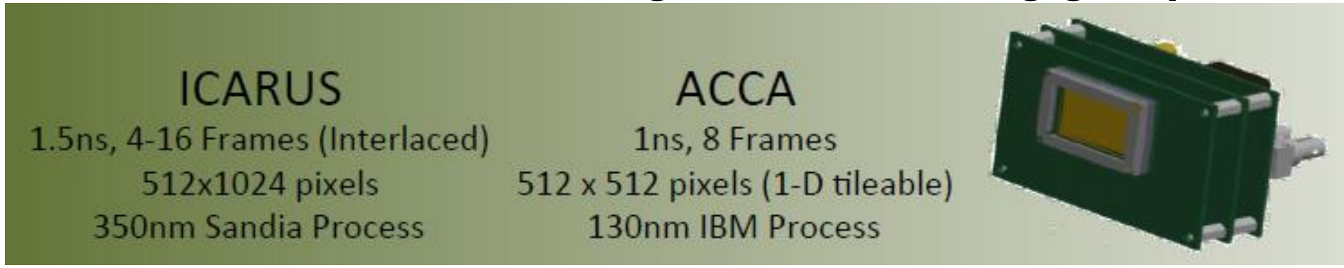


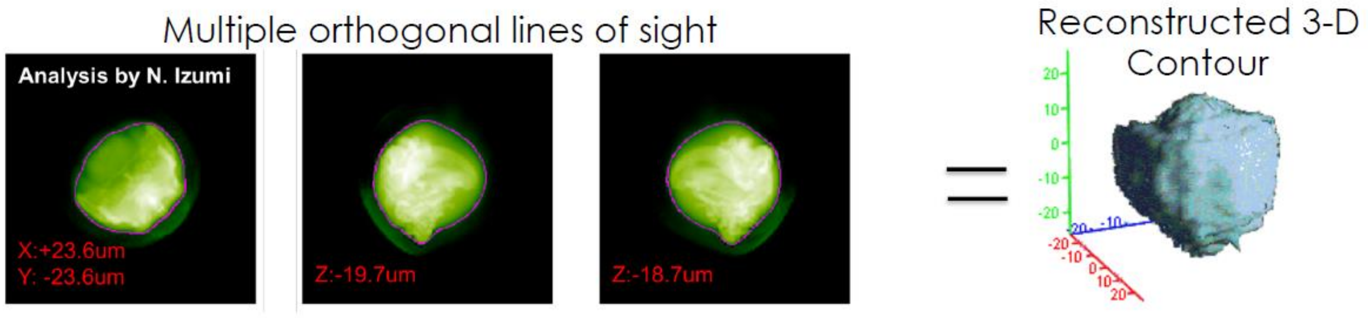
# Development of 3D measurement capabilities is an important thrust since even experiments with a symmetry axis are often 3D

Experiments are 3D!




National Diagnostics Working group

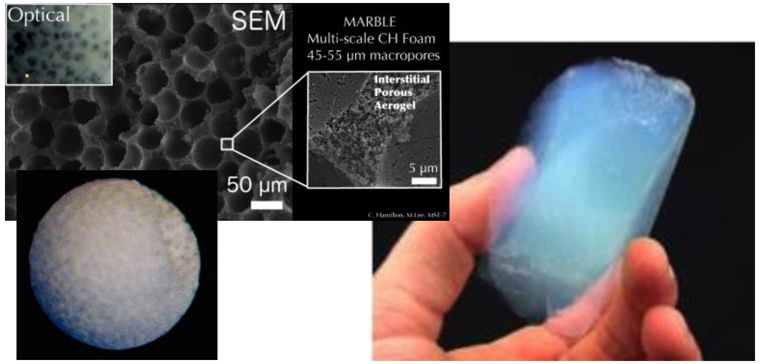


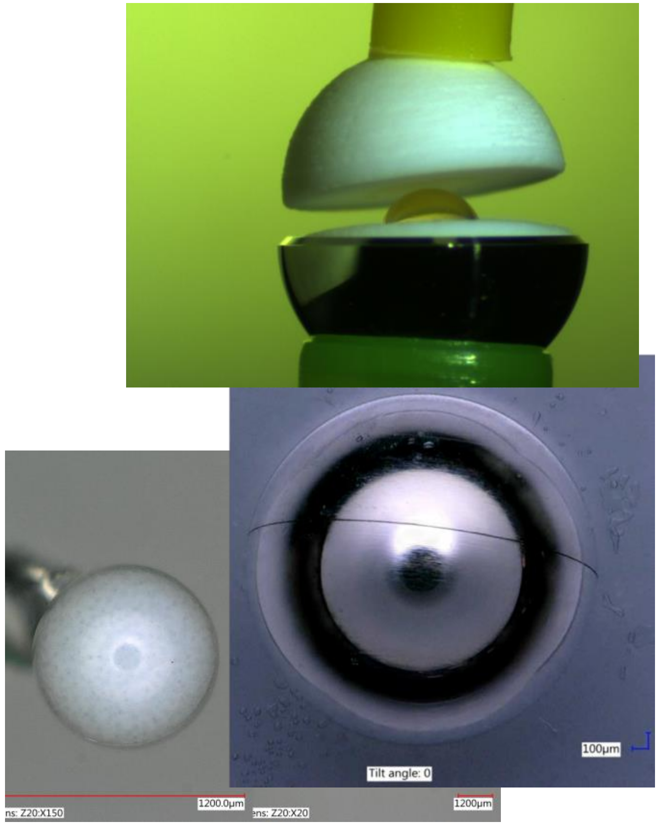

*Izumi (LLNL) et al.

# LANL Target Fabrication Capabilities Include Foam Synthesis & Coatings, Micro-Machining, Precision Assembly and Characterization

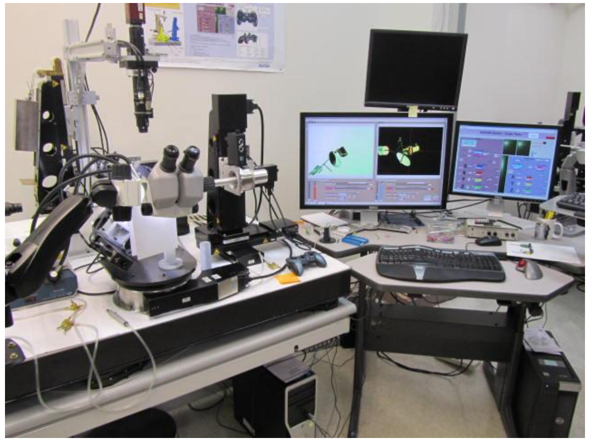
**Many of our experiments require highly specialized <u>Foams</u>**



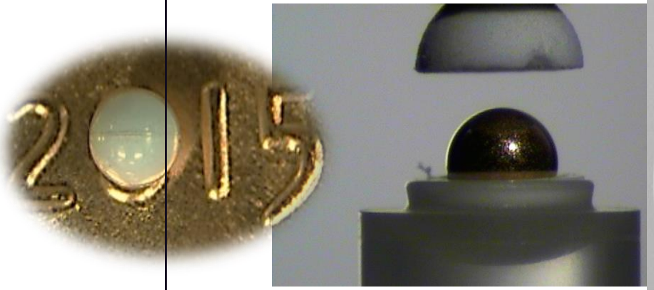

**<u>Micro-Machining</u> of mm scale parts to um precision**

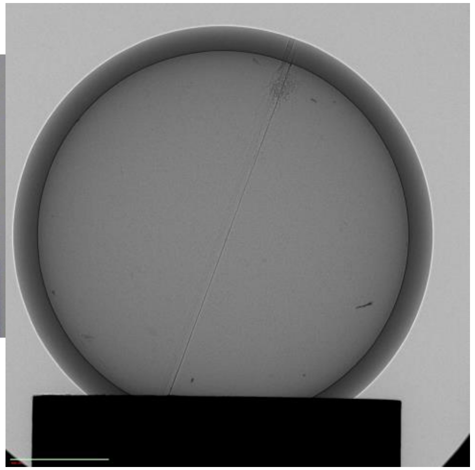



**<u>Precision Assembly</u> is critical for all targets, particularly ones of greater complexity**



**Double-Shell targets require <u>Characterization</u> of centering, density and voids**



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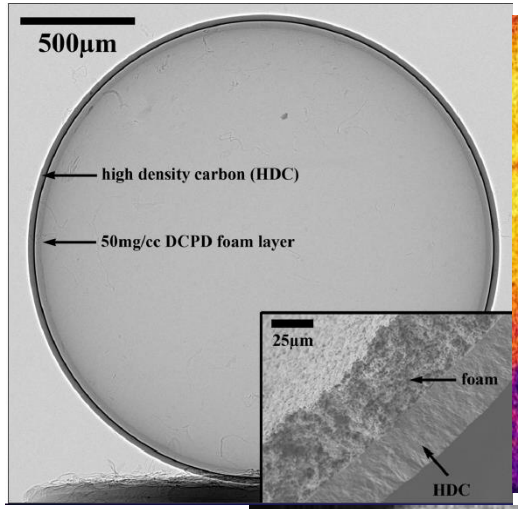
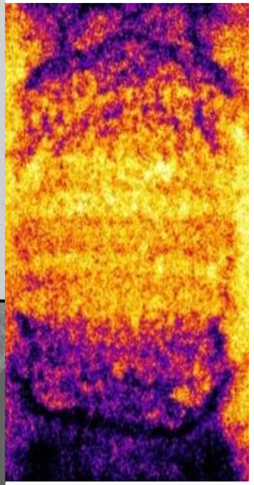
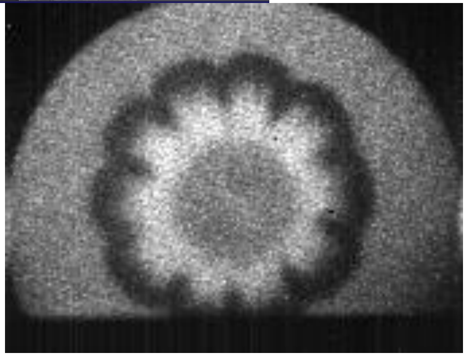
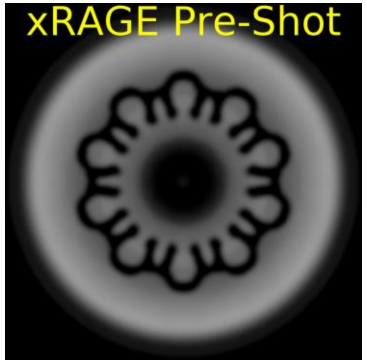
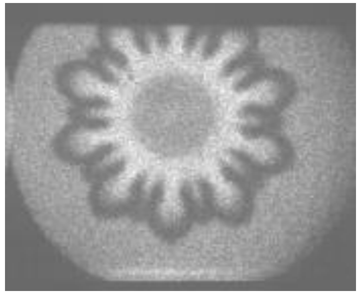


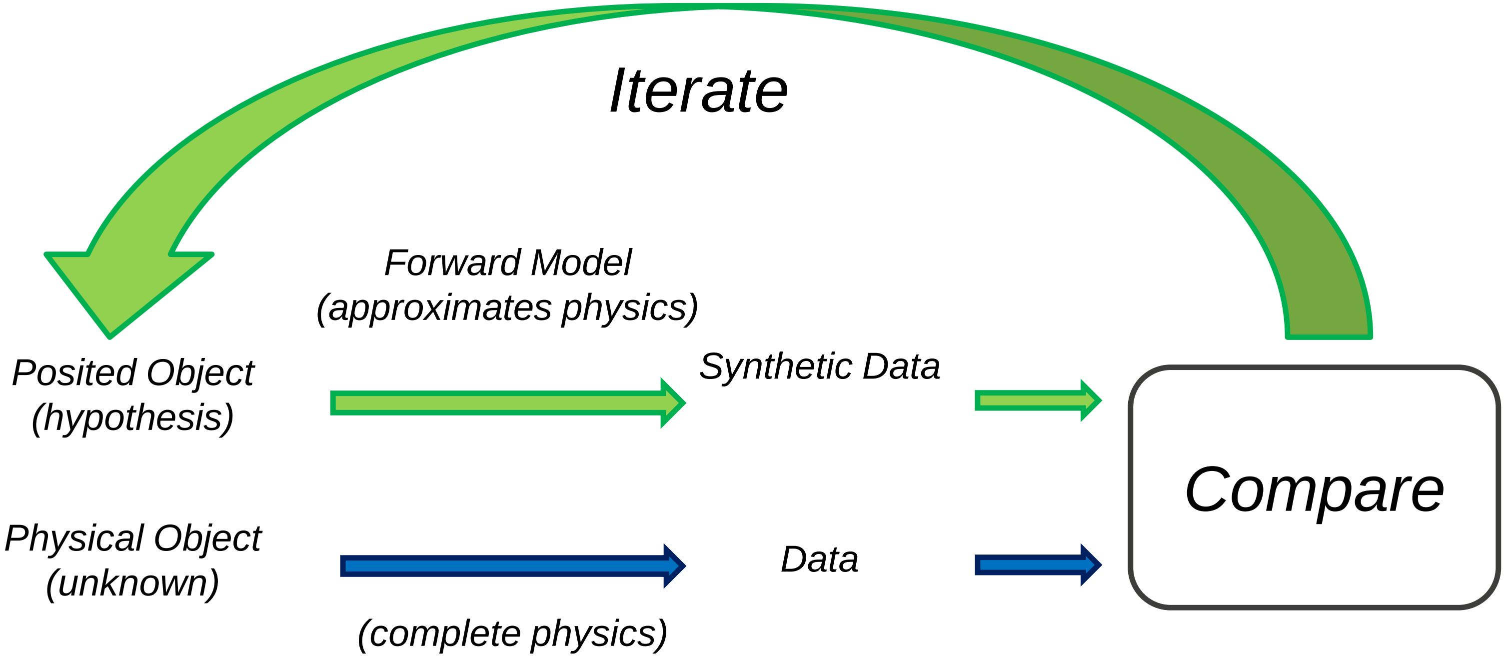





# We are developing more Quantitative Statistical Inference (QSI) methods for uncertainty quantification

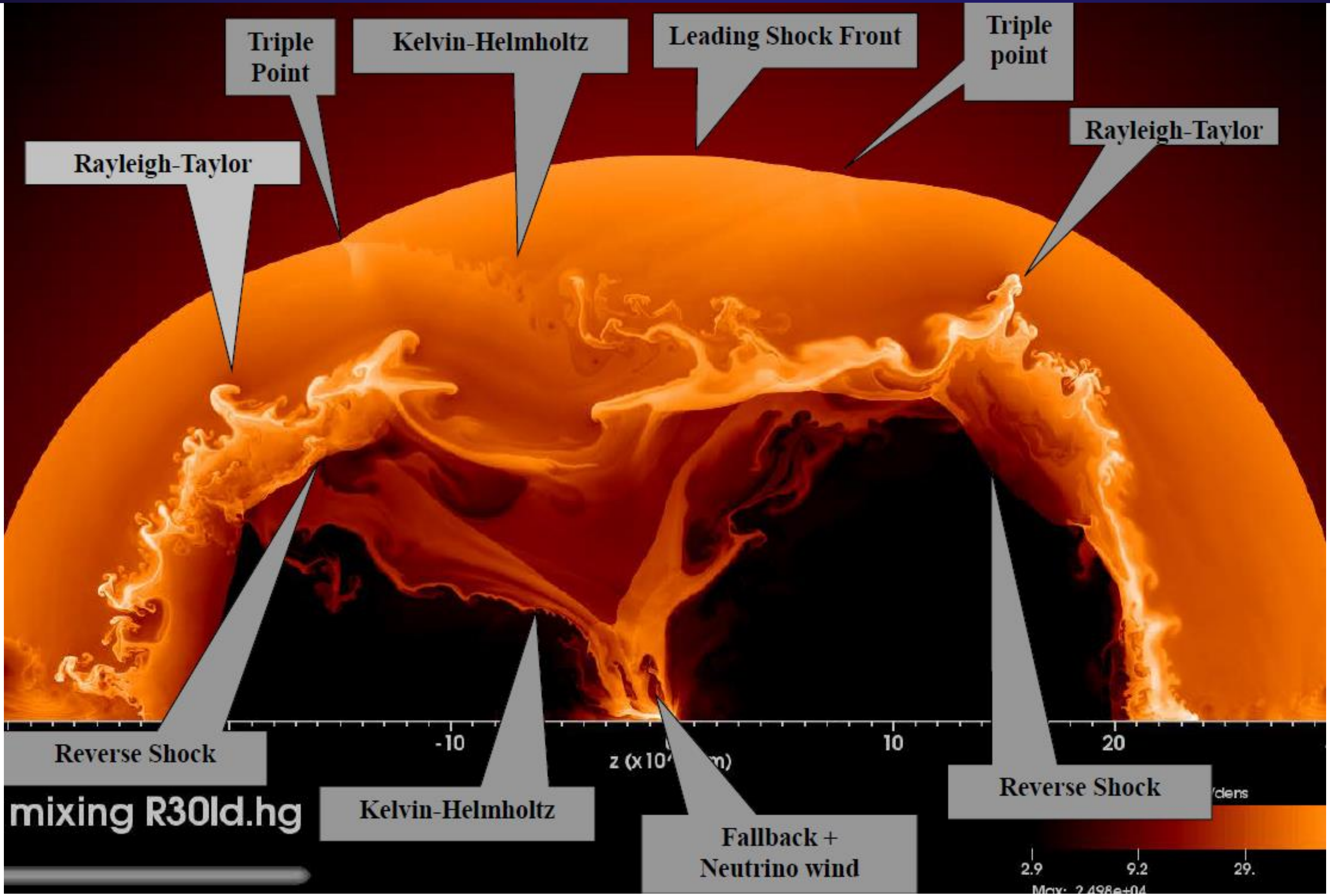





*An iterative method of solving the inverse problem;*
*the best available deterministic solution is often a starting point*

# The work shown here is applicable to other areas of physics (Plewa)



# What is the future:

## HED experiments to become more integrated in fluids understanding how plasmas change the dynamics

- Quantitative evaluation of mix and transition to turbulence:
  - *3D characterization*
  - *Multiple frames for the same experiment to capture 3D evolution*
  - *diffusion*

## Investigating burning plasma:

- Kinetics
- Interplay of mix in the presence of burn

## Applications of ignition:

- Nucleosynthesis
- Nuclear physics
- Nuclear cross sections for burning plasmas

**Turbulence is the most important unsolved problem of classical physics.**
**— Richard P. Feynman**

**"I would ask God two questions: 'Why quantum mechanics, and why turbulence. I think he will have answer for the former.'"**
**W. Heisenberg or Horace Lamb**

# One focus of LANL’s high energy density physics effort is mix and burn during the stagnation phase of ICF implosions

- Inertial Confinement Fusion is a grand challenge in big science requiring a large mix of skills that includes participants both nationally and internationally
- While considerable progress has been made towards ignition, challenges remain which require improved implosion performance or larger capsules
- The largest looming questions are, “Is ignition on NIF possible?” and “What is required to achieve ignition?”
- LANL is strategically focuses on the understanding the evolution of hydrodynamics and burn physics for implosions using novel platforms and focused experiments for code validation
- The program looks to bring in capabilities that can improve our ability to quantify and validate our understanding

Los Alamos
NATIONAL LABORATORY
EST. 1943